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MAY 1955

RATES OF ADVANCE AND RETREAT OF THE MARGIN OF THE LATE-WISCONSIN ICE SHEET

RICHARD FOSTER FLINT

ABSTRACT. Rates of advance and retreat of the margin of a glacier can be calculated from the C^{14} dates of wood debris of forests successively overridden and from other strategically situated samples. Rates calculated from certain Wisconsin glacial fluctuations in central North America are compared with those measured on existing glaciers and are found acceptable under the uniformitarian principle.

RADIOCARBON DATES AND GLACIER MARGINS

One of the several geologic applications of C^{14} dating is the more accurate determination of the rate of displacement of the margin of a glacier as the ice body expands or shrinks. When the advancing margin destroys a forest, the C^{14} date of the woody debris incorporated in the till deposited during the advance approximates the date of the arrival of the glacier margin at the site of the forest. Hence the difference of date of wood samples from two forests situated in the path of advance should approximate the time required for advance from one forest to the other.

The C^{14} dates of many wood samples from till recording a major glacial advance south and west of the Great Lakes region are fully consistent internally (Flint and Rubin, 1955). Hence we can conclude that none of the samples had been carried far by the ice before being deposited. Very likely the region was covered throughout nearly its entire extent by subarctic forest, but whether the forest was continuous or patchy, the C^{14} values date the arrival of the advancing ice margin at the vicinity of occurrence of each sample.

The C^{14} dates of wood samples from sheets of till and bodies of outwash known on independent evidence to be younger than the till of the major advance are believed to record points on the time curve of wavering retreat, punctuated by minor readvances, of the margin of the glacier during the same general episode.

Still other dated samples, incorporated in deposits of a glacial lake, approximate the date of the glacier margin that constituted the northern or proximal shore of the lake, as inferred from the abrupt ending of lake strandlines at the former glacier margin.

As a number of dated samples, embracing the three kinds of occurrences mentioned, are now on record, it is possible to make first approximations to the rates of successive ice-sheet fluctuations in late-Wisconsin time. The present paper aims to do this, and then to inquire whether the inferred rates are reasonable in the uniformitarian terms of known rates of displacement of the margins of existing glaciers.

THE MAJOR ADVANCE

As indicated by Flint and Rubin (1955), U. S. Geological Survey radiocarbon dates (Suess, 1954; Rubin and Suess, 1955) show that a "major advance" occurred in central North America in Wisconsin time. Starting probably from a position north of the Great Lakes, the glacier margin reached the north shore of Lake Erie 27,500 C^{14} yr. ago (W177[1]), passed the site of Cleveland, Ohio, at 24,600 (W71), covered west-central Ohio at 23,000 (W188), neared its mapped southern limit in Ohio, Indiana, and Illinois around 21,000 (W92, 37, 127, 88, 165, 187), and began to recede around 18,000 yr. ago (W91). Various lines of evidence indicate that during this advance the direction of flow in Ohio was southwest and south. Measured in this direction from Cleveland to the outer limit of the Scioto drift lobe, the distance is about 200 mi.; the elapsed time 24,600 minus 18,000 or 6600 yr. The mean rate of terminal advance was then 160 ft. per yr.

It must be kept in mind that rate of terminal advance (the parameter we are attempting to measure) and rate of flow of the glacier body are two different things. Rate of terminal advance (1) is controlled by rate of flow (2) minus ablation losses measured along the ground (3); hence a particular value for (1) tells us only that the value for (2) exceeds it.

It is possible that the general advance was interrupted by temporary retreats. If so, the mean-rate value for advance alone would be increased correspondingly. But in deriving from C^{14} dates a mean value for rate of advance—in this case 160 ft. per yr.—we have to assume that the advance was uninterrupted.

Is this value unreasonably large? The only present basis for judging its reasonableness is comparison with rates of advance of the margins of large, modern glaciers over terrain having very little slope. The present time of world-wide glacier recession affords few examples for comparison. Perhaps the best available is the rate of terminal advance of Black Rapids Glacier, Alaska, in 1936-1937, which was estimated by various observers at 115 to 250 ft. per day (Hance, 1937; Moffit, 1942). The lowest of these values equals nearly 42,000 ft. per yr., about 260 times the calculated rate of the ancient advance in Ohio.

If it is argued that the Black Rapids Glacier advance is a special case, we can use measurements (Field, 1954, p. 237) from the Taku Glacier, Alaska, which has advanced continuously since at least 1900. During a 24-month period in 1950-1952 its terminus advanced at a mean rate of 300 ft. per yr., and during the whole period 1900-1952 its mean advance was 350 ft. per yr. Short-term rates as high as 1650 ft. per yr. have been calculated (William O. Field, unpublished communication).

The rate of advance in Ohio, therefore, lies well within uniformitarian limits.

[1] Prefix *W* indicates samples dated at the U. S. Geological Survey Laboratory. Numbers under 100 are listed in Suess, 1954; those above 100 in Rubin and Suess, 1955.

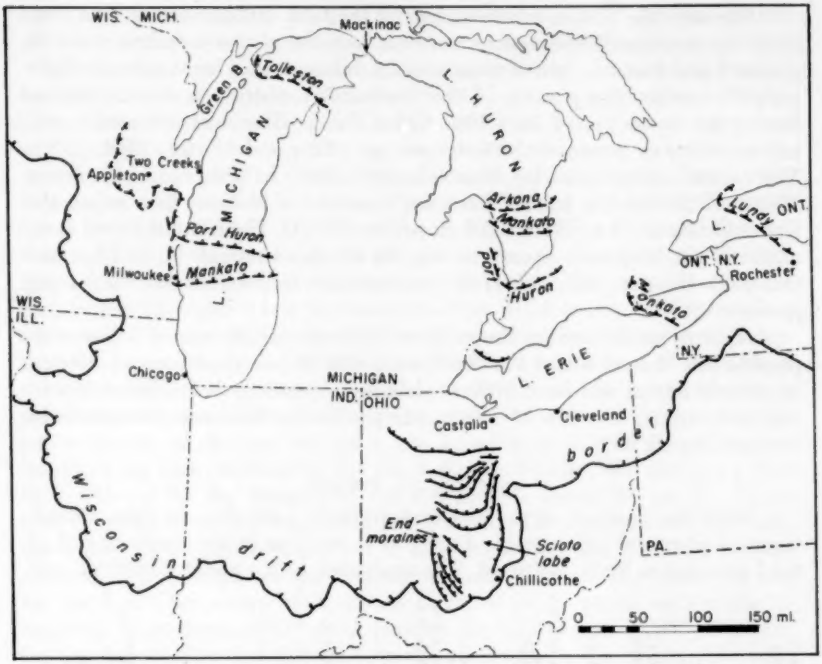

Fig. 1. Sketch map showing localities and principal features referred to in text. Hatched broken lines indicate approximate positions of glacier margin at the times of Lake Arkona, the Port Huron moraine, the Mankato maximum, Tolleston Lake Chicago, and Lake Lundy. Drift border and end moraines from Glacial Map of North America; sources of other data are cited in text.

THE RETREAT FROM OHIO TO LAKE ARKONA

C^{14} yr. ago. The distance from that limit to the position of the glacier terminus in the Lake Huron basin at the time of Lake Arkona is, according to Leverett and Taylor (1915, p. 370), about 325 mi. The close of the Lake Arkona phase occurred 13,600 C^{14} yr. ago (W33; Flint and Rubin, 1955). Subtracting the smaller value from the larger, we get 4400 yr., which measures the retreat. If retreat had been uninterrupted, the mean rate of terminal displacement would have been 390 ft. per yr. But interruptions did occur, because about ten end moraines occur in the Scioto drift lobe in Ohio, and one more occurs in southwestern Ontario (Leverett, 1902, pl. 2). If we allow 50 yr. for the readvance or episode of stability represented by each of the 11 moraines, we must subtract 550 yr. from the gross retreat time of 4400 yr. The resulting value, 3850 yr., applied to the distance of 325 mi., gives a mean rate of retreat of 446 ft. per yr.[2]

[2] W. O. Field suggests that 50 yr. may be an over-generous allowance. He cites conspicuous end moraines formed within less than 10 yr. by glaciers in the Canadian Rockies.

Through the first or southern half of the total distance retreat was over land, but through the second or northern half the glacier terminus stood in glacial Lake Maumee and retreat was by calving. The best-known modern comparisons are the glaciers of the Glacier Bay district in coastal Alaska. During the 8-year period 1899-1907 Grand Pacific Glacier experienced terminal recession at a rate of 5280 ft. per yr. (Tarr and Martin, 1914, p. 8). The corresponding value for Muir Glacier is 5610 ft. per yr. (ibid.). From 1942 to 1950 the rate for the tidewater terminus of McCarty Glacier, on the Kenai Peninsula, was about 4290 ft. per yr. (W. O. Field, unpublished communication). It appears, therefore, that the C^{14}-dated retreat rate in Ohio and Ontario is less than one-tenth of the greatest observed modern rate for calving glaciers.

If, then, we assume for the northern 150 miles of the retreat a rate comparable with that of Grand Pacific Glacier, 5280 ft. per yr., we use up 150 yr. in calving retreat and have 3700 yr. left for a generous 175 miles of slower overland retreat, at a rate of 250 ft. per yr. This is the assumption made in the chart, figure 2.

POST-ARKONA EVENTS

From the position of the glacier margin in Lake Arkona time a readvance of about 60 miles, to the Port Huron moraine at the southern end of the Lake Huron basin, occurred. The readvance began about 13,600 yr. ago

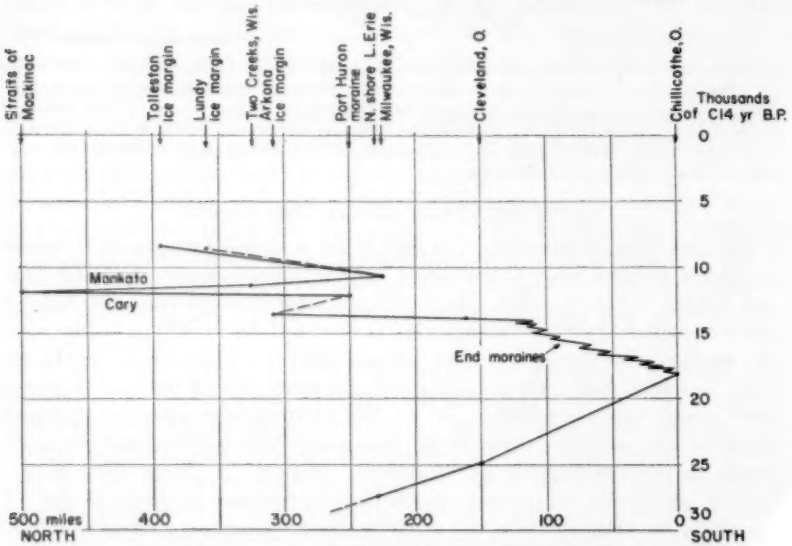

Fig. 2. Chart showing moving positions of glacier margin; north-south distance plotted against time. Because localities in several different lake basins are shown, their relative latitudinal positions are distorted. However, curve slopes show accurate north-south movement rates because each locality is plotted at the correct north-south distance from the preceding point on the moving curve. The coordinates of the chart are reversed so as to place the events in "stratigraphic" sequence.

and ended before 12,200 yr. ago (Flint and Rubin, 1955). In the absence of closer dating we can not derive significant rate values for this readvance.

From the Port Huron moraine, the glacier margin retreated at least as far north as the north shore of the Straits of Mackinac, a distance of 220 mi. This retreat was entirely by calving. If we place the beginning of the retreat at 12,200 yr. ago[3] (existing data do not permit a more exact determination), we have a period of 800 yr. until the well-known spruce forest at Two Creeks, Wisconsin, was overridden by the Mankato (Valders) readvance, an event dated at 11,400 C^{14} yr. ago (Arnold and Libby, 1951; Flint and Deevey, 1951, p. 261). During this period the glacier margin receded from the Port Huron moraine and cleared the Straits of Mackinac. This event lowered the lake in the Michigan basin and permitted the development of a spruce bog on emerged lake sediments at the Two Creeks locality. The glacier margin then readvanced at least 175 mi. from Mackinac to the bog. Growth rings show the oldest measured trees in the bog to have been 142 yr. old when they were overwhelmed. If we allow more than twice this time—300 yr.—for the entire history of the bog, we get a rate of advance of 3080 ft. per yr., far less than the rate observed in the Black Rapids Glacier. We also get a date of 11,700 yr. for the clearing of the straits. This leaves 500 yr. for the retreat from the Port Huron position to the straits. The distance being 220 mi., the mean rate of retreat comes out at 2328 ft. per yr., less than half the rate of retreat by calving observed in modern Alaska glaciers. The calculated rate for the final Cary retreat to Mackinac therefore easily passes uniformitarian scrutiny. As we have no C^{14} check between the 12,200- and 11,400-yr. points, we are free, within the 800-yr. interval, to distribute the events differently from the distribution suggested above. For example, by doubling the rate of calving-retreat (still within uniformitarian limits), we can clear the straits after only 250 yr., and thereby leave 550 yr. for the life span of the bog and reduce the rate of Mankato advance to 1680 ft. per yr. This is a more probable distribution than the one first suggested above, and is the one shown in the chart, figure 2. There remains the uncertainty mentioned previously, however, as to whether retreat began 12,200 yr. ago; the uncertainty can not be eliminated until related C^{14} dates have been obtained.

THE MANKATO MAXIMUM AND SUBSEQUENT EVENTS

The C^{14} date of the Mankato maximum is most closely approximated by a piece of spruce wood from Mankato till underlying sediments deposited in Lake Oshkosh at Appleton, Wisconsin, a water body created by the blocking of a lowland by the terminus of the ice sheet when at its Mankato maximum. The date of the sample (Libby, 1954, C800) is 10,856 $\pm$ 410 yr.[4] At that time the western margin of the Lake Michigan glacier lobe lay across the site of Milwaukee, 100 mi. south of the Two Creeks bog locality. The time elapsed between the advance over the bog and the occupation of the terminal position at Milwaukee is 11,400 yr. minus 10,850 yr., or 550 yr. The rate of

[3] This value is close to that obtained for the beginning of the warm climate in Denmark represented by the Alleröd zone, an approximate correlative of the Two Creeks peat (Iversen, 1953, fig. 2).

[4] This value is close to that obtained for the end of Alleröd time in Denmark (Iverson, 1953, fig. 2).

advance was therefore 960 ft. per yr.—a rate close to that cited for the Taku Glacier during the period 1900-1952. In both instances the glacier margins were advancing through deep water.

The glacier margin in the Lake Michigan basin at the time of the Tolleston phase of Lake Chicago is mapped by Leverett and Taylor (1915, pl. 19) at the latitude of the mouth of Green Bay, 170 mi. north of Milwaukee. A piece of driftwood imbedded in the sediments of Tolleston Lake Chicago, at Chicago, is C^{14}-dated at 8200 $\pm$ 480 yr. (Libby, 1952, C674). Subtracting 8200 yr. from the 10,800-yr. date of the glacier margin at Milwaukee, we get 2600 yr. as the time elapsed during the 170-mile retreat from Milwaukee to Green Bay, and find the mean rate to be 345 ft. per yr. The accuracy of this value is not great because the Green Bay position is known only approximately and because the exact position of the driftwood within the general bracket of Tolleston time is not fixed. As the ice margin can not have been much farther north than Green Bay (Leverett and Taylor, 1915, p. 406), however, the order of magnitude at least is acceptable.

This retreat can be checked by data from the Erie and Ontario basins. A piece of wood from a fossil forest near Castalia, Ohio, submerged by the encroachment of early Lake Lundy and buried beneath lacustrine sediments, is C^{14}-dated at 8513 $\pm$ 500 yr. (Libby, 1951, C526). Lake Lundy and Tolleston Lake Chicago are correlatives. Subtracting 8500 yr. from the date of the Mankato maximum, 10,800 yr., we get 2300 yr., the time elapsed during retreat from the Mankato maximum position in the northeastern part of the Lake Erie basin (Flint and others, 1945) to the Lundy position in the Lake Ontario basin. The latter position is determined by squaring off the ice margin mapped by Leverett and Taylor (1915, pl. 19) from Rochester, N. Y., northwestward to approximate the form of a calving terminus. The distance is 135 mi., and the mean rate therefore 310 ft. per yr. Although subject to the same inaccuracies as that for the Lake Michigan basin, this calculation gives a result of the same order of magnitude.

Several dates of still later events are available (see Flint, 1953, p. 917), but they are not closely enough related to ice-margin positions to be useful for measuring rates of retreat. When suitable samples have been dated, however, approximate rates of still later episodes of retreat can be calculated.

Meanwhile the calculations presented here imply that the C^{14} calendar of late Wisconsin events in the Great Lakes region rests on a sound uniformitarian basis.

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A CLIMATOLOGICAL SURVEY OF THE RETREAT OF THE LAURENTIDE ICE SHEET

GORDON MANLEY

ABSTRACT. For glaciers in temperate latitudes the altitude of the firn line depends on mean temperature during the ablation season (June to September) and secondarily on precipitation. This dependence can be used to estimate the climatic conditions prevailing during the later phases of the Laurentide ice sheet since the Wisconsin maximum. The trends of present-day June-September mean isotherms correspond with the principal drift borders in both North America and northwestern Europe, with similar modifications toward the Atlantic in both regions. These considerations give independent support for correlating Fennoscandian moraines with the Mankato moraine, and permit deductions regarding climatic conditions prevailing near the ice and the time of revival of mountain glaciation in New England and elsewhere. Moreover, height of snowline, mountain glaciation, and the location of the ice-sheet margin can be related to past summer temperatures as indicated by vegetation. As the Laurentide ice sheet was much larger than that of Scandinavia, it took longer to disappear; its post-Mankato fluctuations can perhaps be correlated with minor fluctuations during the earlier Atlantic phase in Europe, before the thermal maximum.

INTRODUCTION

Paleoclimatology is a study in which at first the greater part of the evidence was provided by geologists. With the development since 1921 of the techniques of pollen analysis, botanists have notably increased their contribution. More recently, the advent of radiocarbon dating (Flint and Deevey, 1951) has provided evidence of the broad correlation of certain later phases of the Fourth Glaciation across the Atlantic. Yet some have found it difficult to believe in the coexistence of an enormous Laurentide ice sheet extending to its Mankato limits, and the small Scandinavian remnant in the Finiglacial. In particular, Antevs (1953) has brought forward a series of arguments, based largely on his numerous varve-counts and estimates of rates of retreat, which support the contention that the true equivalent of the Fennoscandian moraines in Europe is represented by the Cochrane position in North America. In the present writer's opinion, however, radiocarbon dates and other evidence show that the Mankato-Fennoscandian correlation, despite its apparent difficulty, should be accepted.

Meteorologists are becoming increasingly aware of what changes can reasonably be expected in the atmospheric circulation, and the extent to which it may be diverted from its present pattern. Moreover, like geologists, they are beginning to find it convenient to adopt the view that the present is the key to the past. In recent years a variety of observations of the behavior of existing glaciers and several studies of the meteorology of ice sheets have considerably clarified the development, maintenance, and waning of the Pleistocene ice sheets.

Suffice it to point to the gradual demise of the exaggerated view of ice-sheet meteorology long maintained by the late Professor Hobbs. While in an earlier climate of opinion it provided a valuable stimulus, one major weakness of his theory indeed arose from the principle of uniformitarianism; when, during the growth of an ice sheet such as that of Greenland, did the grand renunciation of any normal system of falling precipitation occur; when did the

condensation mechanism become the sole source of nourishment; and why should such a process, once established, ever terminate? Ice sheets indeed provide quite a decided impediment to the movement of the surface layers within the general circulation of the atmosphere, but they do not stop the circulation. We now have a far more satisfactory picture of the meteorology of Greenland, and even the much larger Antarctic Continent must, according to Lamb (1952), be traversed by occasional frontal systems.

Evidence on the extent and characteristics of the last phases of the Pleistocene glaciation is now sufficient to enable reasonable estimates to be made of the average meteorological conditions then prevailing, especially in Europe (Poser, 1947; Büdel, 1949; Klute, 1951; Manley, 1951). It is thus becoming possible for the meteorologist, confronted with two or three variant assemblages of the evidence, to say which he will adopt as the more acceptable meteorological picture in the light of current knowledge of the behavior of the atmosphere. The discussion here essayed is based on the spatial-temporal relationships which can be postulated on the basis of present knowledge. The time is ripe for such an assemblage of deductions; for while many details will no doubt give rise to criticism, a stimulus will be given to further scrutiny of one of the world's fundamental problems.

General considerations on summer mean temperatures near the continental glaciers.—The general relationship between the mean temperature at the firn line, or climatic snowline, of the ablation months and the water equivalent of the annual accumulation was expressed by Ahlmann (1948) in a curve integrating for Norway the results of many years of research. Whereas the temperature of the ablation season is the principal factor determining whether glaciers advance or retreat, variations in the amount of solid precipitation are important also. Over considerable areas in which cloudy and windy maritime conditions prevail throughout the year, especially in summer, variations in altitude of the firn line thus represent relative isohyets. Ahlmann's diagram presents two curves referring only to south-central and northern Norway; that is, to a high latitude country with a cloudy maritime climate in which very temperate conditions widely prevail, characteristic of a region in which maritime-polar air masses are dominant and a relatively small part of the ablation can be ascribed to radiation.

Secondly, in temperate latitudes satisfactory estimates can now be made of the mean temperature of the summer months at or close to the border of a large ice sheet. For Europe Klute (1951) and other German writers agree upon a mean July temperature of 5° to 6°C.; (41°-43°F.). As we shall see below, this implies a mean June-September temperature of about 4°C. (39°F.). It is appropriate to examine the question how far similar estimates can be drawn up for North America. Attention is confined in this paper to the Laurentide ice sheet east of 90°W., including the minor contributions from highlands south of the St. Lawrence.

Estimated mean July temperature near the margin of the ice rises as we go eastward in Europe toward drier climates, in which less cloud and more sunshine might be expected. But the annual range of the mean monthly temperature would also increase very sharply; Klute estimated that in north-

central Germany the January mean would be about –22°C. near the margin of the ice, giving an annual range of 28°C. compared with 17°C. at the present day. It is thus evident that the difference between the July mean and the mean for the four months June-September would also be likely to increase with distance from the ocean, as it does today. The present-day difference is about 1°C. (2°F.) in western Ireland, rising to 2°C. (nearly 4°F.) in central Poland. In Europe, therefore, a mean of 4°C. (39°F.) for the four months June-September might be expected to prevail at the limits of the ice sheet.

In North America the presence of a greater ice mass in lower latitudes with more intense sunshine, and the intermittent arrival of humid air from considerably lower latitudes than in Europe, would be likely to lead, in summer, to an even more disturbed and variable climate at the ice margin. For, as the disposition of land and sea was much like that today, with strong solar heating and relatively dry conditions in the southwest, the broad elements of the summer atmospheric circulation south of the ice sheet would also resemble those of today. The movement of humid air from the Atlantic south of latitude 40° and from the Gulf of Mexico would be likely to produce extremely persistent cloud over the margins of the Laurentide ice, and probably heavy precipitation as well from the occluded warm air. Such a scheme of events receives widespread support; the views of Flint (1947), Leighly (1949), and Willett (1950) on the elements of the atmospheric circulation over North America during glacial ages may be cited.

What would happen to the constant descending katabatic wind which the ice sheet might be expected to engender? Studies in Greenland make it clear that at lower levels such constant winds are not to be expected; moreover they are generally shallow (Loewe, 1936). In one of the most exceptionally favorable coastal areas for the development of such winds (Kangerdlugssuak, on the east coast in 68°N.) they were indeed quite infrequent in summer (Manley, 1938), and though within the fiords they were strong at times, much of this might be ascribed to canalisation, which would be lacking around much of the periphery of the Laurentide ice sheet. Moreover the gravitational component on such a gently sloping ice sheet would be relatively small.

In North America as in Europe, clear skies and brisk outflowing winds, becoming extremely turbulent over dry warm ground, might be expected in spring and early summer, favoring the accumulation of loess. Later in the summer the advent of persistent and widespread cloud over the margins of the ice, accompanied by an inversion with warmer air above, would be likely to lead to only shallow katabatics, as the outward radiation from the ice sheet would be much diminished. Accordingly it might be expected that by midsummer the surface-air influence of the neighboring ice would be felt over a narrower zone in North America than in Europe. In consequence, southward rise of average summer temperature in North America would be considerably more rapid than in Europe, and would be steepened by the greater insolation of lower latitudes.

We might thus expect trees, inland, to grow much closer to the ice margin at any stage than they did in Europe. Moreover, the development of small

trees would lead to greater local amelioration of the summer climate, as they would provide an effective check to the intermittent outbursts of the shallow surface stream of air off the neighboring ice, so that, in association with the thinner cloud south of the ice margin, the American sun could get to work in the shelter afforded by the open woodland with agreeable consequences.

It is not easy to give quantitative estimates of these suggested consequences with regard to American vegetation, of lower latitude and of more persistent cloud over the ice for comparison with the North European plains. The situation in Europe is complicated by the existence of the Alps, which would often have acted as a check to the onset of humid air from the Mediterranean, as indeed they do today. At lower levels, convection and condensation were probably the most effective agents of ablation throughout northwest Europe (Ahlmann, 1938), but the supply of summer warmth and moisture as well as summer cloud was largely from the cooler North Atlantic. Radiation would play a greater part farther east, as it does today (Wallén, 1948).

In America convection and condensation losses over the margin of the ice no doubt would be even more effective on account of the greater warmth of the invading moist air masses from the more southerly ocean. In order to ensure maintenance, therefore, it is necessary to postulate heavy summer precipitation at higher levels, which the meteorological scheme above would likewise provide.

Let us now consider some of the deductions arising from the general scheme so far elaborated. At the ice margin, the prevalence of a cloudy and windy summer climate, perhaps even more so in North America, suggests that on either side of the Atlantic in immediate proximity to such vast areas of ice the surface mean temperature, June-September, would be very much the same. Let us therefore adopt 4°C., (39°F.), as a working figure for North America, the primary assumption being that, at the ice margin, the combined results of radiative and advective warmth and of the presence of the adjacent melting ice surface would be the same on either side.

It is now appropriate to review the present day June-to-September means. The following table, based on representative stations close to the former ice margin may be drawn up in round figures:

Present-day mean temperature at sealevel, June-September

	At the Fourth Glacial (Wisconsin) limit	At the Fennoscandian-Mankato limit
Continental Europe	16°C. (61°F.)	15°C. (59°F.)
Continental North America (New York westward)	22°C. (71.6°F.)	20°C. (68°F.)
Toward the ocean:		
England-Scotland	15°C. (59°F.)	14°C. (57°F.)
New England	20°C. (68°F.)	19°C. (66°F.) to 18°C. (64°F.)

In the light of Ahlmann's emphasis on the importance of temperature of the ablation season, it is noteworthy that on both continents the borders of the principal drift sheets lie nearly parallel to the summer (June-September) isotherms, making allowance in Europe for the earlier absence of the North Sea, and in America for the surface effects of the Atlantic and the Lakes at

the present day. Such parallelism is suggestive; it points to the inference that within both continents the general pattern of the summer atmospheric circulation at the Fourth Glacial maximum must have resembled that of today south of the ice sheet, apart from minor surface deviations. This parallelism will be used as a fundamental basis for argument.

It is noteworthy that, compared with the present day, the glacial summer means are lower by 12°C. in Europe and by 18°C. in North America at the ice margin, but only by 9°C. in the central Mediterranean (estimated from Klute's isotherms) and perhaps by a similar amount in Louisiana, decreasing toward the Gulf Coast. Expressed otherwise: in the absence of ice the same sunshine-intensity with a similar distribution of land and sea has subsequently led to a rise of summer temperature, near the ice margin, 50 percent greater in North America than in Europe. From this it is evident that there was also a much larger southward gradient of temperature during glacial ages than at present. In the open plains of Russia Klute put the 10°C. July isotherm about 150 miles from the edge of the ice, and this might well be the outer limit of scattered trees. In the light of the much more rapid gradient of summer temperature likely to prevail, it would thus be reasonable to suggest that inland in eastern North America trees might well be found within 80 miles

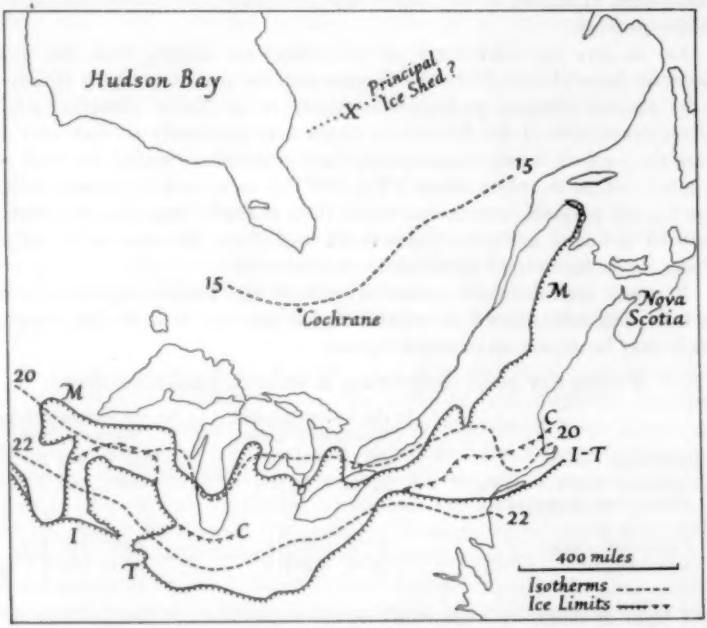

Fig. 1. Present-day isotherms June-September . . . 22°, 20°, 15°C. (sealevel). Positions of ice margin after Flint: I-T = Iowan-Tazewell, C = Cary, M = Mankato. Radial distances, from *X* in the direction of Maine, 900±, 850±, and 650 miles; toward New York, 1030, 910, and 800 miles; toward Illinois, 1300, 1150 and 1040 miles; Cochrane, about 540 miles.

of the ice margin, with well-developed forest not far beyond. Such a deduction receives support from the evidence (Deevey, 1953).

Close to the Atlantic coast, however, there would be more cloud and wind for a greater distance south of the ice. Hence the width of the "tundra" zone would probably be considerably greater than inland; moreover, the "cold wall" off the New Jersey coast would also be broader, giving rise to increased low stratus cloud in summer throughout New Jersey and perhaps into Delaware. The associated extension, thanks to the cooler summer, of "periglacial" phenomena southward into Virginia can well be explained; a July mean temperature of 48-49°F. in southern New Jersey does not seem impracticable.

On the above arguments it would be reasonable to expect that the forest would approach most closely to the ice along the flanks of the sheltered valleys in the western Allegheny Plateau. It would also appear that with greater distance from the Atlantic the skies would be clearer and the glacier wind would thus be stronger in summer. If that were so the tree line might be expected to retreat farther from the ice margin. The distance of the tree limit from the Des Moines glacier lobe may be particularly significant, as there is reason to believe that the exceptional advance in this region might be ascribed to excess of precipitation in association with a low-index situation (Leighly, 1949) and possibly a greater relative excess in winter. This argument is further considered below.

Snowlines and upland glaciation.—The curve constructed by Ahlmann (1948) shows that in a maritime region in high-temperate latitudes with high precipitation, such that the water equivalent of the snow accumulation amounts to 100 inches, a firn line or climatic snowline should be found where the mean temperature of *June-September* is 3.6°C. (38.5°F.). This of course is a very heavy precipitation; and in regions where more precipitation falls in summer than in winter. it might well imply that the total amount, i.e. including rain as well as snow, was as much as 150 inches.

If we halve this total, the mean summer temperature at the firn line falls to about 0.7°C. (33.3°F.). If the mean summer temperature at the ice margin is 4°C. (39.2°F.) the firn line or climatic snowline should thus be found at about 550 meters (1800 feet). Such an altitude might reasonably appertain to places in high latitudes with 75 inches of precipitation annually, measured as water, and with a well-marked maximum in the summer months. In the latitude of New York it might be expected to lie rather higher on account of the additional ablation due to radiation, even in a cloudy climate.

In drier regions the firn-line temperature, June-September, tends to be appreciably below 0°C. (32°F.) If we assume that in drier climates a firn line occurs about the level where the July mean equals 0°C. as is broadly true of central Greenland and of the drier parts of the Alps, we might put its altitude at the Wisconsin maximum as high as 3700 feet above sealevel in the drier Middle West, for example. But in such an event the annual precipitation would be much lower, perhaps of the order of 30-40 inches (cf. the rise in the snowline from Fanaråken to Glittertind in Jotunheim).

Field evidence suggests that a snowline at some intermediate level, say 3000 feet, would be acceptable in the region of the Catskills; here, local cirques were developed perhaps before overriding by the greater Laurentide ice if there was enough time, and were reoccupied by local glaciers which descended some way toward the lowland in the Tazewell and Cary sub-ages of the Wisconsin.

Thus, reversing the argument, if a careful analysis were made, based on field investigation in such smaller highland areas, of the extent of locally derived ice in relation to the probable snowline, it might be possible to make estimates of the annual precipitation and also of the duration of the periods of advance.

No sign of cirque development has been found farther south, even on the Allegheny Plateau. Marginal forms may perhaps be present in northern Pennsylvania, but the general lack of cirques implies a snowline well above 2500 feet.

Consideration of an altitude varying from, say, 2300 feet in coastal New England to 3000 feet in the Catskills and the Allegheny Plateau, in relation to the probable slope of the ice sheet, would appear to indicate that in summer the firn line would lie between 100 and 200 miles upstream from the glacier margin, and possibly as much as 300 miles in, say, Iowa, where the gradient would be particularly gentle. Such very wide ablation areas would give rise to vast volumes of meltwater.

Farther north, the glacial phenomena in New England deserve correlation. In the first place, we have the field evidence (cited by Antevs, 1932) that late in Wisconsin time some of the cirques in the White Mountains were reoccupied by small glaciers. These must have been "marginal," and from discussion with Dr. R. P. Goldthwait it must be conceded that some at least may have been little more than large residual and inactive snowbeds, giving rise to protaluses. Nevertheless the existence of small moraines, possibly in part protaluses, at about 3700 feet in Tuckerman Ravine, and 3600 feet in King Ravine, where the back walls rise to well above 5000 feet, can be taken as evidence that in these cirques the average altitude of the snowline for a considerable period lay at about 4600 feet. Precipitation in this area today is heavy (82 inches on Mount Washington) and accordingly the June-September mean temperature at the snowline might fairly lie in the neighborhood of 2° to 2.5°C. (35.5° to 36.5°F.), with a corresponding July mean of 38°-39°F.

If that were so, the mean July temperature at 700 feet would stand about 52°F. and would be compatible with the growth of birches in the upper Connecticut valley. Farther north, however, at the same altitude in northern Maine, it is probable, from the appearance of the present-day isotherms and the likelihood of a rather steeper northward gradient of temperature than prevails today, that the mean for July would be appreciably below 50°F., a figure compatible with the lack of trees in the post-Alleröd or Mankato sub-age recognized in the Aroostook County region (Deevey, 1951).

It thus appears undeniable that the last very small cirque glaciers in the White Mountains developed in the Mankato sub-age. Support for this scheme of temperatures is also forthcoming from Mount Katahdin, where Antevs

(1932) described the last cirque moraines at about 2500 to 2900 feet; from an inspection of the map it appears that glaciers of this extent would be maintained with a snowline at about 3500 feet. Given the fairly high precipitation which Katahdin appears to have today, such a snowline would be compatible with a June-September mean of 35°F. and a mean July temperature at 600 feet, the level of Deevey's Aroostook ponds, of 47°F. or thereabouts. This again suggests correlation of the last local glaciers with the Mankato. Moreover, between New Hampshire and Maine, snowlines at these altitudes differ by just about the amount that might be inferred from the present-day summer isotherms. This would lead to the opinion that small glaciers would be found in the Adirondacks but not on the Green Mountains (J. W. Goldthwait, 1915, p. 73) and certainly not on the Catskills. This appears to be in good agreement with the suggestions made by Flint (1953, pl. 2).

Moreover the northward fall of summer temperatures thus indicated would make it reasonable to place the Mankato snowline on the Shickshocks at about 2300 feet. With such a snowline, the width of the broad tabular summits of this range is sufficient to ensure that they would sustain an extensive local ice cap, and the supply of ice would be large enough to spread down to the adjacent lowlands in both directions. Such a scheme would agree with the field evidence discussed by McGerrigle (1952) and with Flint's inferences (1953); and on the south side resembles the scheme of events adjacent to the Catskills earlier in Wisconsin time.

From an inspection of air photographs of the Shickshocks, an opportunity which I owe to Professor F. K. Hare, and from discussion with authorities who know the range, it appears that "last moraines" are probably to be found at an altitude of 2500-3000 feet, near the levels of the floors of the existing cirques. These, if corroborated, must appertain to a stage in which the snowline was considerably higher than that postulated for the Mankato above, and their possible correlations are discussed below.

The orientation of the best-marked cirques in these mountains is N.N.W. rather than N.E. Perhaps this points to the predominance of S.E. winds accompanying the heavier snowfalls, especially in summer. Also the mean temperature, June-September, at the summit is about 42.5°, if extrapolation from nearby stations beside the St. Lawrence shore is valid. This would lead to the possibility that one or two permanent snowbeds might today survive in sheltered gullies, the necessary mean to ensure such survival being about 42°F. (Manley, 1949). No adequate gully, however, appears to be found beside the highest summits, and from discussion it appears that the range just fails to harbor any such marginal remnants, other than in occasional cold summers; this view is supported by McGerrigle (1952). For a natural thermometer of this sort, the mountains of southeastern Labrador may be better situated.

Southward rise of mean summer temperatures at maximum glaciation.— Earlier in this paper it was deduced that the rate of rise of temperature southward from the margin of glaciation was a good deal more rapid than at present.

We have seen that cirque development in the Catskills and the spread of local ice therefrom are compatible with a snowline approaching 3000 feet and a mean temperature (39° June-September) of about 43° for July at the ice margin.

There appears to be no report of cirque development in the high southern Appalachians; hence the snowline there is very unlikely to have descended below 6500 feet. This would agree with a mean June-September temperature of *at least* 56° at sealevel and a July mean of 60° or above. This implies a northward fall in the summer mean temperature of 17°F. in 6° of latitude, a gradient fully twice that which prevails today in the same region. This lends support to the earlier estimate that trees grew in the Ohio region at a distance of not more than 80 miles from the ice, and probably somewhat nearer in sheltered places.

Let us now see where these considerations will take us in relation to post-Mankato time.

Post-Mankato events and the final waning of the ice sheet.—It has been demonstrated that the post-Alleröd climatic recession in Maine is best correlated from the climatological standpoint with the Mankato readvance in the Michigan region. Moreover, if snow were then accumulating on the Shickshocks above 2300 feet it would be difficult to avoid the conclusion that following the summer isotherms snow would likewise be accumulating on the surface of the ice sheet still covering the "height of land" north of Lake Superior-Georgian Bay, and nourishing the ice in the Michigan region.

Flint (1953, p. 898) mentioned evidence of lesser readvances postdating the Mankato maximum. A paper by Antevs (1953) emphasized, with numerous references, the existence of extensive moraines in the Cochrane region, implying an oscillation of some magnitude, corresponding in his view with the Fennoscandian-Salpausselkä moraines in Europe. It would be wrong to avoid the question raised by these moraines, as they appear to indicate a condition of stability or readvance large enough to have widespread effects. It is thus necessary to consider what, if any, possible correlative exists in Europe.

A remnant ice mass centered in the James Bay-Labrador region should, by analogy with earlier conditions, be expected to possess a margin broadly parallel to the present-day pattern of the summer isotherms. The present mean sealevel temperature, June-September, near Cochrane is about 15°C. (59°F.); this isotherm, representing the four-month ablation period, runs eastward south of Lake Mistassini and toward the north shore of the Gulf of St. Lawrence. Hence if ice still lay near Cochrane, its margin upon the upland north of the Gulf would suggest that at sealevel the June-September mean would not then exceed 6°C. (43°F.) and July would not exceed 8.5°C. (47°F.)

Further: if the interpretation of the last small moraines at about 2500 to 3000 feet in the Shickshocks is correct, it suggests a minor halt or slight readvance of the local cirque glaciers with a snowline around 3300 feet. With a snowline at this altitude, the sealevel mean for July would be about 49°F. It might thus be reasonable to consider a correlation of these last small active

cirque glaciers in the Shickshocks with the July sealevel mean of 47°F. in Southern Labrador proposed in the previous paragraph. As the climate near the Gulf would thus be marginal for tree growth, the possibility exists that evidence of such a minor climatic recession might be sought in the birch pollen in Gaspe. Such an event might be expected to occur after the ingress of the Champlain Sea while it was still cold. That small local glaciers might be revived under such conditions on the Laurentides north of Quebec city (Flint, 1953) would also appear likely, as their height is much the same as the Shickshocks; and although they lie farther south, precipitation is relatively heavy (Hare, 1951).

Yet if it does become necessary to postulate one or more post-Mankato stages of stability or readvance, the evidence of steady warming during the Boreal in northwestern Europe is such that transatlantic correlation will be difficult unless a minor recession of brief duration developed before the thermal maximum during the earlier Atlantic phase; for this there may be some tenuous evidence, possibly between 5000-4500 B.C. (Brooks, 1949). Here the suggestion by Conway (1948) of an interval of about 900 years between such recessions might be quoted; and at a time when eastern Canadian summer temperatures were lower than now, a small increase in precipitation during a century or so could impose a decided check on the retreat of the margin of the remaining ice, while elsewhere remnant snowbeds would revert to active glaciers. Although the evidence shows that in eastern Canada the summers at the thermal maximum were warmer than today by 4°F. in July (Hare, 1952), which is noticeably similar in amount to the July warming in Denmark (Iversen, 1944), this warming west of the Atlantic appears to have been attained somewhat later than in Europe.

As regards timing, a period of 3500 years for the retreat from Lake Michigan to Cochrane (about 500 miles) would perhaps be sufficient to satisfy requirements, having regard to the accelerating retreat that one would expect with the rapidly diminishing elevation of the ice remnant across the "height of land" south of Cochrane; and it would be compatible with such estimates as can be made of the bulk of the ice remaining to be melted. These arguments, however, in the present state of knowledge, are not strong, and they may well be amended when further field evidence is forthcoming.

In the light of the recent announcement of a radiocarbon date of peat near James Bay (Potzger and Courtemanche, 1954), namely, 2350 years ± 200 B.P., giving evidence that white pine and some southern broad-leaved genera had by then extended their range to James Bay but have since retreated southward about 350 miles, it would now be very difficult to correlate the glacial readvance which the evidence at Cochrane described by Antevs appears to demand, with the sub-Atlantic recession in Europe; and correspondingly, re-establishment of glaciation anywhere in southern Quebec at such a late date appears to be impracticable. It would seem more reasonable to expect a relationship with a much earlier recession antedating the thermal maximum, as indicated above.

Some meteorological inferences.—From what has been said it appears that the several positions of the ice margin represented by the known read-

vances are closely associated with the trend of the summer isotherms (June-September): 22°C. (or 71.6°F.) for the Iowan-Tazewell, slightly lower for the Cary, and about 20°C. (68°F.) for the Mankato. To this might be added 15°C. (59°F.) for the readvance that appears to be represented at Cochrane.

Let us consider the nature of the Mankato readvance. If it is true that the readvance in the region of Lake Michigan was of the order of 275 miles in distance (Flint, 1953, p. 907), the ice spread from a position where the present mean summer temperature at sealevel is about 64°-65°F. to where it is 68°F. (18°-20°C.). The present-day pattern of the summer isotherms is indicative of the main sources of heat, radiative and advective, and it might thus be suggested that a fall of the order of 4°F. (2°C.) in the summer means would be enough to provide for this readvance. But this is not likely; such a fall of temperature would probably be enough to provide for *maintenance* at the advanced stage, but not actual *rapid growth*. It seems more reasonable to suggest that during the major advance evidenced at Two Creeks, the temperature at least for a time fell farther and was associated with a decided increase in precipitation as well. We must envisage a long series of dull, cold summers with abundant precipitation, bringing the snowline far down toward the margin of the ice. It is noteworthy that exceptionally cold summers within the range of the instrumental record have been characterized by falls of the order of 5°-6°F. in the mean temperature.

And yet, if the meteorological factors at work, such as a long-lasting change in the zonal index, were sufficient to lower the mean temperature by 6°-7°F., then, even in the absence of secondary effects resulting from the greater area of the ice, the cooling would be almost enough to allow of *maintenance* of the ice sheet at its farthest Tazewell limit. That some very sharp cooling took place before the arrival of the ice appears to be borne out by the evidence of the tree rings at Two Creeks.

Very similar arguments can be put forward with regard to ice advance in England. The evidence favors the view that for maintenance of the known vegetation of the Alleröd phase in the Lake District a mean June-September temperature of about 50°F. would be required (Manley, 1951), whereas the same isotherm would appear to have retreated southeastward by about 250 miles (about 4°F.) in the post-Alleröd movement to which the Fennoscandian moraines bear witness. But the re-establishment in England and Wales of many mountain glaciers would appear to demand a considerable period with a greater fall of temperature, and it is demonstrable that a fall of a further 4°F. would be compatible with *maintenance* of an ice sheet of much greater extent (Newer Drift in England, for example). The quantities on either side of the Atlantic, crudely resolved though they are, are sufficiently similar in magnitude to render it likely that the same ultimate causes were operative.

Moreover, this parallelism between the deductions on either side is not only striking but leads to the conclusion that, allowing for some secondary cumulative effects, each of the glaciations—Mankato, Cary, Tazewell—arose from a fall of temperature initially of the same order of magnitude, but lasting for a longer time. Such a deduction is in accordance with the view expressed by Faegri (1950) who approached the problem from the standpoint of a

botanist. If so, it is for the meteorologist to consider what factors might lead to the zonal index retaining a bias on one side or another for lengthy periods.

Characteristics of the retreat.—The overwhelming evidence that over long periods of time the Laurentide ice sheet diminished by thinning begs the question how this could happen. The necessary heat might be provided by radiation and by convection including condensation; but in cloudy climates at lower levels the latter appears to become the principal factor in ablation (Ahlmann, 1938). Steady downmelting therefore would appear to demand a rise in temperature of the principal source of warm moist air, that is, the subtropical Atlantic; this might be equally effected by a broadening of the surface area of the warmer water. Likewise, the views of Mannerfelt (1945) regarding downmelting of the Scandinavian remnants must be recalled; he too demands increasing convection-loss arising from a warming air supply. But if the latter must largely come off the North Atlantic Ocean, it would appear to require that the ocean surface began to warm up first, perhaps by the northward spread of waters of more southerly origin; and a like process might be postulated on the American side with a narrowing "cold wall." This introduces oceanographic problems beyond the scope of the present discussion.

The repeated retreats and slight readvances to which the moraines in Indiana bear testimony seem adequately explained as the result of the small climatic fluctuations of the order of a decade or two in length such as we observe within the instrumental period. With an ice sheet of such size as to be capable, apparently, of advancing or retreating by a mile in a single year, and with a dynamic climate arising from the low latitude in which minor vicissitudes would have maximum effects, it is not difficult to conceive such results, and to allow for the local overriding of remnants of dead ice from time to time, to assist the explanation of the complexities of the drift.

Dating of events.—The lag in the disappearance of the Laurentide ice sheet, by comparison with Europe, arose from its greater size. If we assume wastage by downmelting to have been dominant, we may also assume that, with the steady eating away of the periphery of the ice sheet, the summit altitude would diminish. It is probably simplifying the picture altogether too much to suggest, as the diagram (fig. 2) does, that the decline of the summit level proceeded *pari passu* with the retreat of the margin. Yet if the zone of maximum snowfall lay at an altitude well below the original summit level, such an assumption is not difficult to maintain. Moreover, subsidence of the summit level might be expected, as such a vast dome of ice several thousand feet thick would lack the lateral support provided by peripheral mountain systems such as we observe in Greenland. Further, with gradual rise in temperature a corresponding rise in the plasticity and consequent freedom of motion toward the ice margin might be expected. It is quite impossible to imagine that with an ice margin near Cochrane the ice divide could still have stood at 10,000 feet; by then it would have been much lower.

If the hypothesis of diminishing thickness represented by the diagram is true, it would suggest at once that nearly three-fifths of the total original volume of Wisconsin ice south of the ice divide had disappeared by Two

Creeks time, and nearly two-fifths in the Mankato. But part of the ice sheet lay on an already elevated plateau, 1000 to 2000 feet or more above sealevel. Hence it would be fair to say that south of the ice divide any residuum with a margin near Cochrane possessed but a small fraction of the original volume.

Earlier in this discussion it was observed that the fall of temperature postulated to provide for the vigorous Mankato advance might almost have been enough, if sufficiently prolonged, to maintain glaciation at its maximum extent; more especially if secondary effects arising from the increase in the area under ice are allowed. Hence if the volume of the Laurentide ice sheet increased by between 1/10 and 1/5 during this advance, which appears to have occupied about 500 years, continuation of the advance to the position of the outer Wisconsin drift border, if such had occurred, might have required about 2500 to 5000 years during which meteorological conditions remained favorable for growth. But if it is subsequently shown that the Mankato re-advance took place more rapidly, and was followed by a period of stability, the above crude estimate will need revision. Deductions based on estimates of the amount of precipitation are not easily made, for we lack knowledge of the part played by the motion within the ice mass in maintaining the forward position.

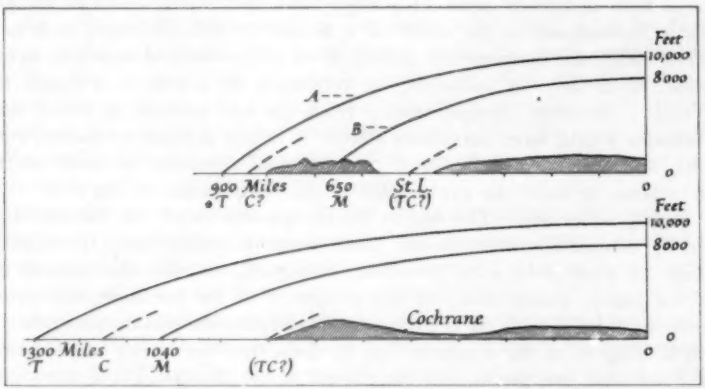

Fig. 2. Hypothetical profiles drawn on the Laurentide Ice Sheet from *X* (fig. 1) 900 miles southeastward to Maine, and 1300 miles southwestward to Illinois, at various maxima and one minimum during the Wisconsin age. T = Tazewell; C = Cary; TC = Two Creeks; M = Mankato. A = altitude of Mt. Washington; B = altitude of Shickshock Mountains. Uplands beneath the glacier are shaded.

The simplicity of the picture shown in figure 2 has appeal, yet may be the more dangerous on that account. Moreover, if the ice margin lay on the upland north of the Gulf of St. Lawrence, any small fluctuation in precipitation in this region would lead to appreciable advance. Such an ice remnant standing above the present plateau would receive more orographic precipitation than the present-day plateau margin, on which precipitation is quite large even now (Hare, 1951). Hence it seems practicable to envisage a very late

phase of glaciation with ice moving both southward and northward from the high ground of southeastern Labrador.

Thus for a brief interval before final deglaciation, the ice divide might well have migrated south of the latitude (55°N) indicated by Flint, providing a likelihood of a brief revival of local glaciation among the summits of the Laurentides (3900 feet) north of Quebec City. But it would again be difficult to consider such a revival unless the mean July temperature at, say, Quebec fell below 55°, with a corresponding fall to 50° or lower near the mouth of the St. Lawrence.

We have already seen that such a readvance would more easily be correlated with the latest glacier development on the Shickshocks, which in turn would agree best with an early period in the existence of the Champlain Sea.

Some consequences of the presumed rate of melting.—It has been shown that the present-day normal summer heating in North America at the Wisconsin limit now provides, from June to September, about 86°C. (155°F.) of accumulated warmth in month-degrees above the freezing point; whereas at the limit represented by the Pomeranian-Danish-Newer Drift limits in Europe the corresponding figure is about 64°C. (115°F.). Cloudy, windy and dull summers on either side of the Atlantic tend to be about 2°C. (or 3.5°F.) below the normal, suggesting that the ratio between the accumulated warmth on the two sides of the Atlantic in particularly cloudy seasons is about 78/56 or 1.4 to 1. It would seem that, to a first approximation, the corresponding rates of removal of ice by downmelting in the cloudy glacial-age summers lay in roughly the same ratio.

Using the data given by Flint (1947, p. 434) and assuming that at the Mankato maximum in America about half the total volume of Laurentide ice south of an ice divide at 55°N had been melted, this might well amount to 8 or 9 million km^3. At the corresponding Fennoscandian maximum in Europe it would appear that about four-fifths of the Scandinavian ice south and east of the ice divide had been melted, say 6 km^3, during the same interval of time. These figures are rough, being derived from eye estimates based on small scale maps, but they are of the right order. In other words there remained in North America between four and five times as much ice to be removed as in Europe, southward from the respective ice divides, and on the above assumptions it would take fully three times as long. Hence assuming 1600 years in Europe for final removal to the stage of small mountain remnants, the last extensive relics of the Laurentide ice might, all other things being equal, be expected to disappear by about 3000 B.C.

The crudity of such estimates must be emphasized; and an additional factor likely to cause the last remnants of the ice south of Hudson Bay to disappear more quickly is that on its north side the ice would be lapped by an extensive body of water with a broader outlet to the Atlantic than exists today. Such values would however allow for the requisite development of a thermal maximum in southern Quebec well before 1000 B.C.

Assumptions on the above lines, like others in this paper, must be rough in the extreme in our present state of knowledge and beg many questions;

but they are offered in order to provoke discussion and closer analysis of the probabilities inherent in the available data. It does appear that the dimensions of the several quantities are of the right order.

To provide such predominance of downmelting over several thousand years meteorologists will need to explore further the dating of the changes of temperature of the surface waters of the North Atlantic (Wiseman, 1954). For, by analogy with what happens in East Greenland today (Manley, 1938) the presence of a broad belt of pack ice off Labrador and around Newfoundland would undoubtedly diminish the precipitation reaching the coast north of the latter island; so that the zone of maximum frontal activity and accompanying precipitation would probably lie to the south, much as it does today. It is possible that the latest episode of glacier activity might be attributed to the increasingly ice-free character of the Champlain Sea in summer, with consequent increase in precipitation locally.

Overall estimates of summer and winter mean temperatures at the Wisconsin maximum.—It has already been proposed that an appropriate July mean for the New York region would be 43°F. and that, near the ocean, the mean was still below 50° in southern New Jersey. A July mean of the order of 51°-53° might be expected around Pittsburgh and westward, at points 80-100 miles from the ice margin. A July mean at sealevel of *at least* 60° in the southern Appalachians is called for in view of the lack of evidence of glaciation. On the same parallel of 35° latitude, the evidence of the snowline suggests that in New Mexico the present summer mean temperature was lowered by a broadly similar amount (Stearns, 1942). Thus, from the Ohio River the southward temperature gradient of mean July temperature would have been fully twice its present value, so that toward the Gulf Coast the July temperature should exceed 70°; this appears to conform with the indication given by Deevey (1949, p. 1375).

In winter, assuming that permanently frozen ground occurred in central New Jersey, a mean January temperature of 10° would be appropriate here, and along the Ohio. Such temperatures are not very far below those of the coldest winters in the instrumental record and, by analogy, it would appear that January means of the order of 35°-40° could be sustained from Louisiana to southern Alabama. Such a southward gradient in winter would not differ seriously from that which obtains today, and would accord with our knowledge of the character of the air masses likely to be involved.

Consequent lowering of the mean annual temperature would be about 13°F. near the Gulf, 16°F. in 35°N., rising to 20°F. in the Ohio valley and 27° at New York. Lowering of the snowline would be about 4000 feet or a little more, both in the southern Appalachians and in New Mexico, and probably 6000 feet or a little more in New England and beyond. Hence the snowline would be found virtually at sealevel around the mouth of the St. Lawrence and around James Bay. These findings appear to be abundantly confirmed by our knowledge of the extent and character of glaciation toward the coasts of Newfoundland.

SUMMARY OF CONCLUSIONS

1. Difficulties in correlating late- and postglacial events on both sides of the Atlantic can largely be resolved if account is taken of the great volume of the Laurentide ice sheet.

2. The dependence of altitude of firn line on mean summer temperature during the ablation season, and secondarily on precipitation, is observed. The correspondence between present-day mean summer isotherms and the outer margin of extensive glaciation during the glacial ages on both continents is linked with the conclusion that the successive positions of the ice-sheet margin during deglaciation lie approximately parallel to the present summer isotherms, apart from minor coastal effects.

3. In eastern North America, away from the coast, forests probably were nearer the margin of the ice sheet than in Europe.

4. Links can be established between height of snowline, development of mountain glaciation, position of the ice-sheet margin, and mean summer temperature as indicated by the vegetation.

5. It appears likely that the last small mountain glaciers were re-established in the Catskills during the Cary sub-age; in the White Mountains in the Mankato; and in the Shickshocks, somewhat later.

6. It appears that the Mankato readvance resulted from a fall of temperature which, if sustained, might well have sufficed to carry and maintain glaciation as far as the Iowan-Tazewell limits; but it did not last long enough. That the Mankato ice virtually reached the Tazewell limit in the Des Moines lobe supports the view that the readvance was associated with a low-index meteorological situation prevailing over a considerable period, with an excess of winter (snowy) precipitation toward the southwestern flank of the ice sheet, and an excess of summer precipitation farther east which at lower levels might in part be rain.

7. Relative to the present day, the fall of temperature was much more marked in summer in eastern North America, and in winter in northwestern Europe.

8. Studies of present-day records indicate that quite small fluctuations appear to be synchronized on both sides of the North Atlantic (Hare, 1952; Manley, 1954). Present evidence suggests that readvances that postdate the Mankato are likely to be equated with one of the minor climatic recessions in Europe during the Atlantic period.

FINAL REMARKS

The above broad scheme of events, estimates, and correlations appears to develop logically from what is known of the behavior of glaciers and the character of deglaciation, and from analogy with events in northern Europe. It is acknowledged that considerable speculation is involved in the later stages of the discussion.

With the steady progress of field research amendments to these broad-scale findings will become necessary from time to time.

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STUDIES IN THE SYSTEM $CaO—MgO—CO_2$
PART 2
LIMITS OF SOLID SOLUTION ALONG THE BINARY JOIN $CaCO_3$-$MgCO_3$*

R. I. HARKER and O. F. TUTTLE

ABSTRACT. The subsolidus relations in the system $CaCO_3$—$MgCO_3$ have been examined between 500 and 900°C. and it is found that solid solutions containing up to 24 percent by weight of magnesite (or 52 percent of $CaMg(CO_3)_2$) in calcite are stable at 900°C. and at pressures sufficiently high to prevent the dissociation of the carbonates. Metastable solid solutions between calcite and dolomite have been synthesized and found to contain 64, 77, and 86 percent by weight of the dolomite composition, suggesting that complete solid solution between $CaCO_3$ and $CaMg(CO_3)_2$ may be found at higher temperatures. There is evidence of slight solid solution of calcite in both dolomite and magnesite, but the amount of magnesite in solid solution in dolomite was found to be always less than 1 percent in the 500 to 900°C. range. No ordering of Ca and Mg has been observed in either the calcite or the magnesite solid solutions and it is possible that a "dolomite" with the calcite structure may be stable at high temperatures (i.e. disordered $CaMg(CO_3)_2$).

INTRODUCTION

During the course of investigations into the subsolidus phase relationships in the ternary system, synthetic calcites were grown in equilibrium with dolomite. The X-ray powder diffraction patterns of these calcites did not exactly correspond to that of pure calcite. The positions of the calcite peaks were observed to be shifted to higher angles, i.e. toward the corresponding peaks of magnesite. This suggested that some calcium in the calcite was being replaced by magnesium. Goldsmith and Graf (1953) have observed that, in calcites formed at temperatures above the stability field of dolomite and in fact developed as a result of the dissociation of dolomite, some of the calcium is replaced by magnesium.

Experimental details and results.—The synthetic work to be discussed in this paper was carried out in cold-seal pressure vessels to which a pressure of CO_2 was supplied by means of a hand-operated hydraulic pump. The entire apparatus has already been described in some detail in Part 1 of "Studies in the System CaO—MgO—CO_2" (Harker and Tuttle, 1955).

In order to verify that the modification of the calcite lattice was due to a partial substitution of calcium by magnesium, carbonate mixes were made up of the following compositions:

Mix no.	Percent by Weight $CaCO_3$	$MgCO_3$
1	100	0
2	99	1
3	98	2
4	96	4
5	92	8
6	84	16
7	68	32

* Contribution No. 54-22 from the College of Mineral Industries, The Pennsylvania State University.

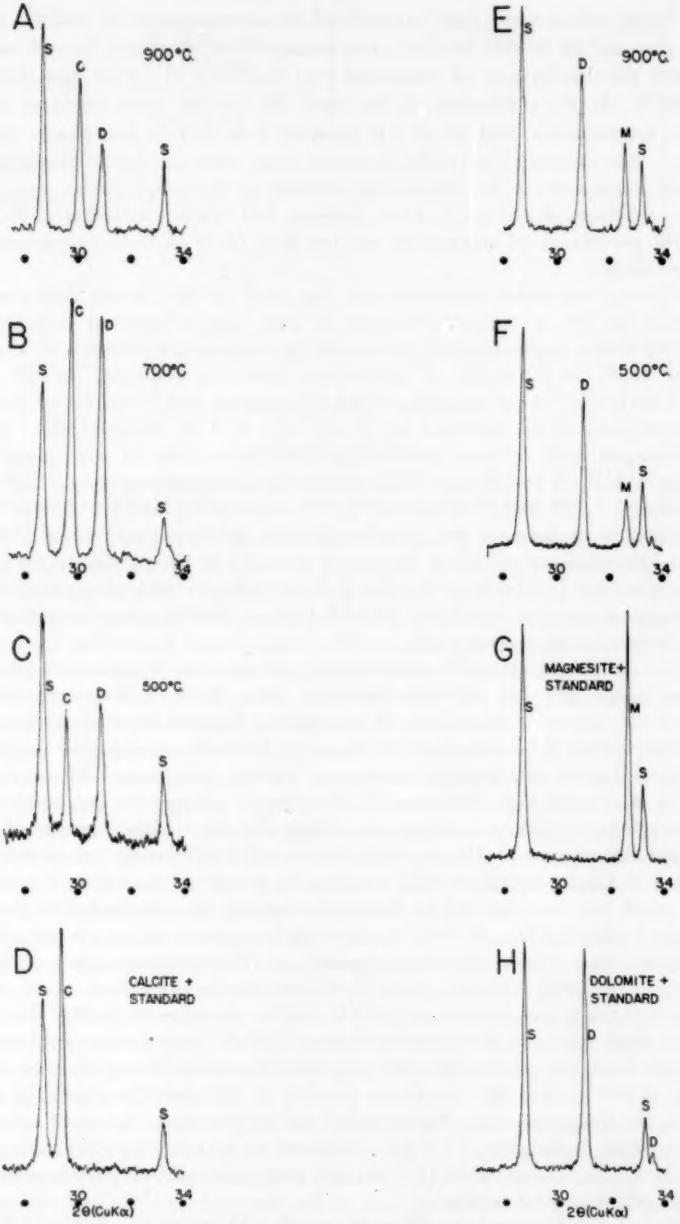

Fig. 1. X-ray powder diffraction patterns characteristic of the products of runs made in the investigation of the limits of solid solution in the system $CaCO_3$—$MgCO_3$. S = Standard (CdF_2), C = Calcite, D = Dolomite, M = Magnesite. (Radiation CuK_α).

These mixes were then crystallized at a temperature of 800°C. and a CO_2 pressure of 30,000 lbs./in.^{2}: this pressure was found to be sufficient to prevent the dissociation of magnesite and therefore of calcite and dolomite at 800°C. At the conclusion of the runs, the samples were analyzed on an X-ray spectrometer, and in all the samples 1 to 6 only one phase, namely calcite, was present. The peaks, however, were seen to change progressively toward magnesite as the magnesium content of the original mix increased. In the products of mix no. 7, both dolomite and calcite co-existed, indicating that the percentage of magnesium was too high for it all to be accommodated in the calcite.

Having concluded therefore that the shift in the calcite peaks was a function of the magnesium content, it was next considered desirable to establish some rapid method by which the magnesium content of a given calcite could be estimated. A convenient standard, cadmium fluoride, was mixed with each of the products of the above runs, and it was found that the strongest peak of the standard lay at an angle of 0.72° of 2θ (CuKα) below the strongest peak of pure calcite and 3.96° below that of pure magnesite. In figure 1 D, G and H the (211) peaks of calcite magnesite and dolomite are labeled C, M and D respectively: The standard peaks are labeled S. It was possible to measure the angular distance between peaks to $\pm 0.01°$ of 2θ by always using points at the center and at half the height of the peaks in question and by checking that the distance between the two standard peaks was constant (and in fact 4.55° 2θ with CuKα). This accuracy was found to be sufficient for the present work.

The values for the differences in 2θ between the positions of the carbonate peaks and the stronger standard peak, $2\theta_{c\,(211)} - 2\theta_S$, were plotted against the known compositions of the calcites formed from the mixes 1 to 6 inclusive, with the result shown in figure 2. It can be seen that all the points corresponding to the various calcites of known composition lie extremely close to a straight line. Moreover, if this line is produced it passes through the point corresponding to magnesite. Using this line it has been possible to estimate the amount of Mg as magnesite in solid solution in calcite and the amount of Ca as calcite in solid solution in magnesite to within 1 percent. This graph has been utilized to determine the variation in the limits of solid solution in the $CaCO_3$—$MgCO_3$ system with temperature. The procedure was as follows. Two mixes, one approximately of 70:30 and the other of 30:70 by weight of $CaCO_3$: $MgCO_3$, were placed together in a pressure vessel which was raised to a temperature of 800°C. and a pressure of 30,000 lbs./in.^{2}. In both these mixtures there was an excess of the dolomite component, causing the growth of this phase and insuring that the solubility which was determined at 800°C. was the maximum possible in the time for which the runs were made. The runs were then repeated for longer times and until no more solid solution took place. This was presumed to give the equilibrium values for 800°C., i.e. calcite with 17.5 percent magnesite and magnesite with 1.5 percent calcite in solid solution.

For runs at lower temperatures, it was possible to approach the solubility curves from both sides. For example, in the case of calcite, two charges were

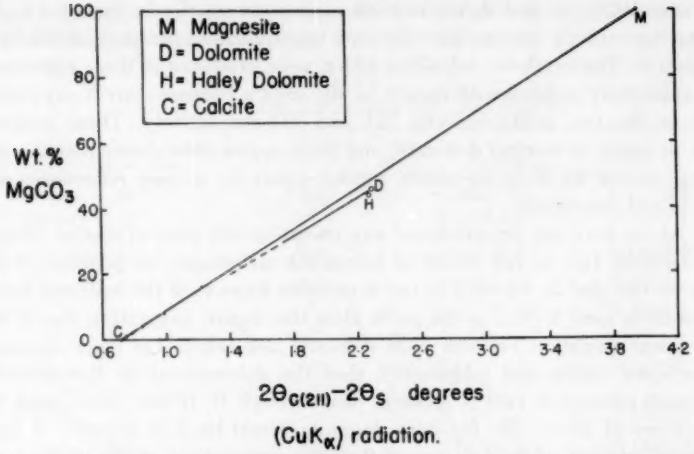

Fig. 2. Graph for determining the composition of the phases in the system $CaCO_3$—$MgCO_3$ from the position of the (211) reflections relative to a standard.

put into one pressure vessel, the first containing a calcite-rich carbonate mixture and the second containing a sample of the magnesium-rich calcite (+ dolomite) formed at a higher temperature. In the mixture, the initially pure calcite would take magnesite into solid solution, while the magnesium-rich calcite which had been formed at higher temperatures would, by a process of exsolution, become less magnesium-rich. If at the end of the run the composition of the calcite in the two crucibles was the same, then it was assumed that equilibrium had been attained.

Runs have been made as high as 900°C. where a pressure of just over 40,000 lbs./in.^{2} was necessary to prevent the decomposition of the magnesite of the mixtures. It was not possible to make runs for more than about half an hour at these temperatures and pressures, and we could approach the curves only from their convex side. It is probable, however, that the points plotted are close to the correct position for the equilibrium compositions because they are derived from the results of several experiments.

Figure 1 illustrates some of the typical X-ray powder patterns from the products of these runs. It will be observed how the angle $2\theta_{C(211)}-2\theta_S$ increases with temperature in the series A to D. The percent of $MgCO_3$ in A is 19.5, in B - 11, in C - 5.5, and in D - 0. The shift of the dolomite peaks in this series and of the magnesite peaks in E, F and G can be determined only by measurement of the original patterns, whereas no shift was detected in the dolomite peaks in patterns E, F and H.

The limits of solid solution of calcite and magnesite in dolomite were determined in a similar manner to that in which the limits of solid solution between calcite and magnesite were determined. It was, however, not possible to use the straight line between calcite and magnesite in figure 2 in order to determine the compositions of dolomite. The structure of dolomite, space group R $\bar{3}$, is ordered with respect to the Ca and Mg atoms (Wyckoff and

Merwin, 1924) so that dolomite itself cannot necessarily be expected to have d spacings exactly intermediate between the equivalent spacings of calcite and magnesite. The synthetic dolomites which were produced in these experiments are apparently ordered with respect to Mg and Ca because their X-ray patterns contain the two peaks indexed 221 and $11\bar{1}$ respectively. These peaks are seen to occur in natural dolomite, and their appearance shows that the space group cannot be R $\bar{3}$c in which q must equal 2n in ppq reflections, as in calcite and magnesite.

As we have not yet produced any unequivocally pure synthetic dolomite, i.e. dolomite free of any relicts of unreacted carbonates, the position of dolomite on the plot in figure 2 is not accurately known. If the analyzed natural dolomite is used it plots at the point H in this figure, suggesting that if there is a linear variation between pure dolomite and calcite (as there appears to be between calcite and magnesite), then the dolomite-calcite line should, if the small amount of FeO is ignored, pass through H. If this line is used, then the values of $2\theta_{C(211)}-2\theta_S$ for pure dolomite would be 2.34 degrees. If this is the true relation, then it is found that the composition of the dolomites in equilibrium with magnesite at different temperatures is consistently on the calcite side of pure dolomite, which is improbable. That part of the solvus which defines the amount of magnesite which can be taken into dolomite in solid solution is unlikely to be on the opposite side of the ideal dolomite composition from magnesite. As there is no apparent change with temperature in the amount of magnesium contained in the dolomites associated with the magnesites, this part of the solvus must be a vertical line at least between 500 and 900°C. It was considered that the most reasonable answer to the problem was to regard the amount of solid solution of magnesite in dolomite as negligible, i.e. that in dolomites formed in the presence of excess $MgCO_3$ the atomic ratio Ca:Mg is 1:1. This suggests that the analysis of the natural dolomite H is only 1 percent off composition with respect to the $CaCO_3$: $MgCO_3$ ratio, ignoring the small amount of FeO. A slight excess of $CaCO_3$ may well be in the form of calcite in the sample analyzed. If the above interpretation of the facts is correct, then $2\theta_{C(211)}-2\theta_S$ for pure dolomite is 2.30 degrees. The line joining this point to calcite was used to determine the various compositions of the dolomite in equilibrium with calcite at different temperatures.

A summary of the data obtained from the runs made to locate the lower temperature part of the solvus in the system $CaCO_3$—$MgCO_3$ is given in table 1, from which figure 3 has been drawn.

It is considered likely that at slightly higher temperatures the solid solution between calcite and dolomite may be complete provided that melting at a eutectic composition between calcite and dolomite does not intervene. Although, owing to the high pressures needed to prevent the dissociation of the dolomite, we have not been able to make runs at higher temperatures than 900°C., in some of the runs at this temperature metastable carbonates have been prepared having compositions lying in the two phase region, as indicated by the open circles in figure 3. If there is a complete dome of exsolution between calcite and dolomite, it will probably be complicated by

the order-disorder transition which would take place somewhere between the calcite solid solutions and dolomites.

TABLE 1
Solid Solutions in the System $CaCO_3$—$MgCO_3$

Run	Initial Materials	Temp. °C.	Time hrs.	Products		Wt. %
1	C (xs) + M	900	0.5	C (24% M)	+	D (43% M)
2	M (xs) + C	"	"	M (2% C)	+	D (45.5% M)
3	M (xs) + C	820	4	M (1.5% C)	+	D (46% M)
4	C (xs) + M	800	8	C (16% M)	+	D (43.5% M)
5	"	"	48	C (17.5% M)	+	D (43.5% M)
6	"	"	120	"		"
7	C (xs) + M	700	240	C (11% M)	+	D (43.5% M)
8	C (16% M) + D (43.5% M)	"	"	"		"
9	M (xs) + C	"	"	M (1% C)	+	D (45.5% M)
10	C (xs) + M	600	14	C (8.5% M)	+	D (44% M)
11	"	"	44	C (8% M)	+	D (44.5% M)
12	"	"	576	C (7% M)	+	D (44% M)
13	M (xs) + C	600	576	M (0.5% C)	+	D (44.5% M)
14	C + M	500	60	C (5.5% M)	+	D (44% M)
15	C (16% M) + D(43.5% M)	"	312	C (5.5% M)	+	D (45% M)
16	M (xs) + C	"	576	M (0% C)	+	D (45.5% M)

C = Calcite
M = Magnesite (xs) = excess over dolomite composition.
D = Dolomite

All runs were at pressures between 45,000 and 20,000 lbs./in.^{2} as necessary to prevent the dissociation of the carbonates.

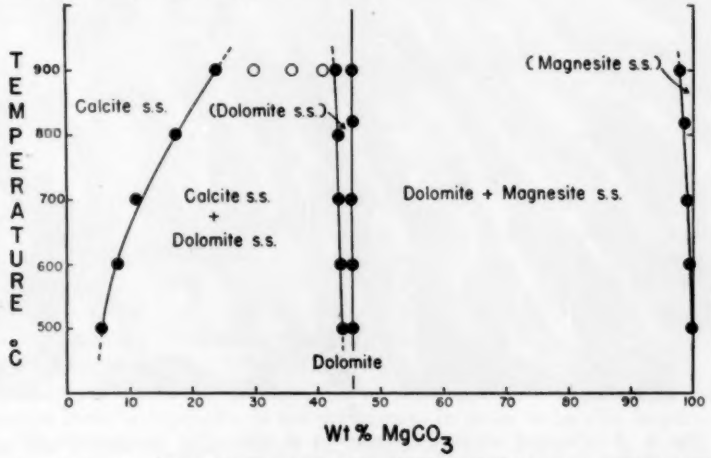

Fig. 3. Limits of solid solution in the system $CaCO_3$—$MgCO_3$ between 500 and 900°C.

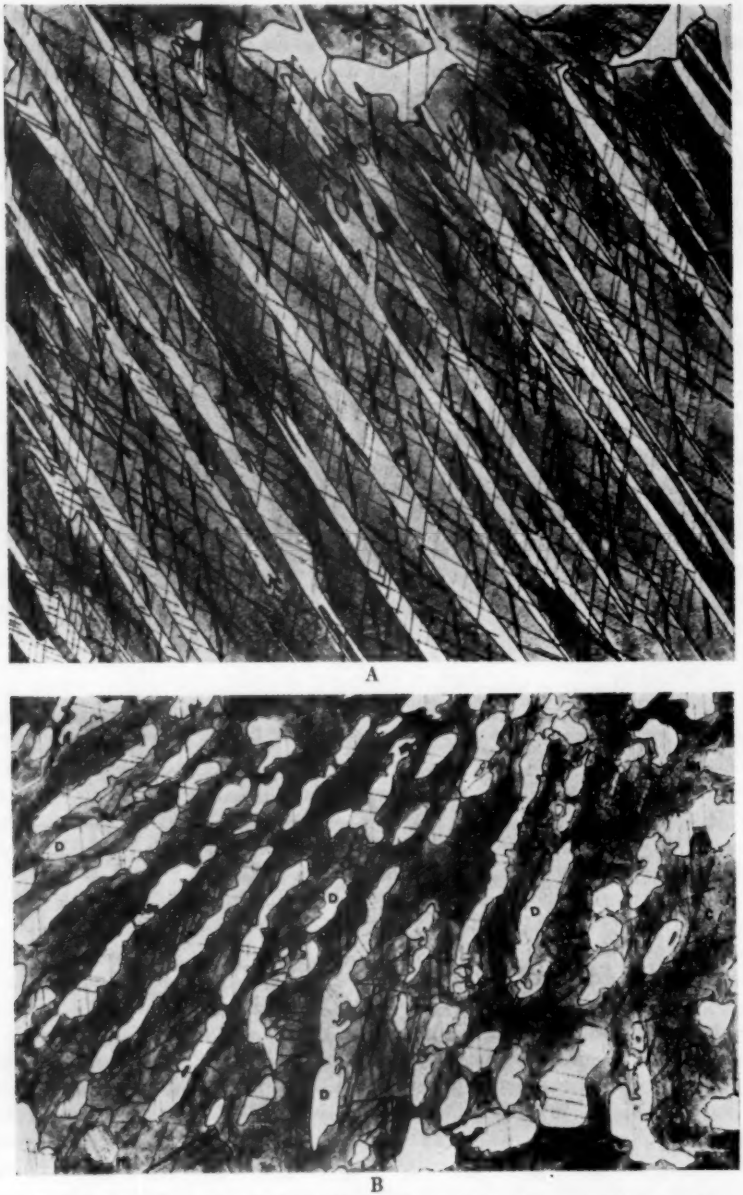

Fig. 4. Parallel and ramifying intergrowths of calcite (C) and dolomite (D). The calcite is stained dark by Lemberg's solution (Coomaraswamy, 1902).

4A. Magnification is × 20; 4B. Magnification is × 9.4.

Petrological considerations.—The subsolidus relations in the $CaCO_3$—$MgCO_3$ system are not without geological significance, but it is necessary to add a note of caution on the limitations involved in their application. The relatively large change in the amount of magnesite which can be taken into solid solution in calcite over a range of temperature which is probably not infrequently encountered in regions of metamorphism in the Earth's crust raises the hope that the Mg:Ca ratio in the calcite of dolomitic limestones could be used as a geological thermometer. The idea is enhanced by the probability that the degree of solid solution is insensitive to pressure provided that the pressure is sufficient to prevent dissociation of the carbonates.

In certain cases it would not be unreasonable to infer that the temperature so deduced was the minimum temperature to which the rock had been subjected during its metamorphic history. The comparative ease with which exsolution can be effected in the laboratory makes it unlikely that in nature carbonate rocks would usually be quenched sufficiently rapidly from their highest metamorphic temperatures to prevent any unmixing on cooling. Indeed it is highly probable that not only would a carbonate solid solution unmix but the components might well become segregated completely to form separate crystals with no evidence of ever having existed as a single phase. Many analogous examples have been described for the feldspars. (e.g. see Tuttle, 1952).

It is not surprising therefore that the number of recorded instances of carbonate intergrowths possibly due to exolution is comparatively small. Coomaraswamy (1902), describing the carbonate rocks intimately associated with charnockites and pyroxene granulites in Ceylon, has illustrated two excellent examples which are reproduced in figure 4. The other minerals in the carbonate rocks include diopside, forsterite, spinel and phlogopite. Explanations other than one of exsolution may be justified to account for these calcite-dolomite intergrowths, but Coomaraswamy noted that they are invariably of dolomite in calcite and he says "it is exceedingly rare to meet a reverse relation." From what is now known about the subsolidus relations between $CaCO_3$ and $CaMg(CO_3)_2$ a calcitic host is to be expected if the intergrowths are due to exsolution. It is possible that the conditions of metamorphism in the granulite facies were sufficiently dry to prevent the carbonate phases from becoming segregrated into completely separate units after unmixing.

At Ben Bullen in New South Wales Joplin (1935) has described myrmekite-like intergrowths of dolomite in calcite in carbonate rocks which are almost completely engulfed in a quartz-bearing pyroxene diorite. The quartzose shales in this region are represented by cordierite hornfelses. Again it is likely that the intergrowths are due to exsolution, for Joplin observes with reference to the calcite-dolomite intergrowths that "in every known occurrence of this structure calcite is the host."

The $CaCO_3$: $MgCO_3$ ratios in the calcite and in the dolomite which comprise these intergrowths is not yet known. In order to be able to estimate even the minimum temperature of metamorphism, however, it would be necessary for the carbonates of a dolomitic limestone to be sufficiently pure

to be regarded as occurring in the $CaCO_3$—$MgCO_3$ system at least until the effect of iron and other components on the solid solution is known.

It would also have to be borne in mind that the Mg:Ca ratio in calcites may be relatively high by virtue of other factors than a subjection to elevated temperatures. For this reason it would be important not to select samples of unrecrystallized limestones likely to have been formed by biological action (Chave, 1954).

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GENESIS OF JADEITE BY LOW-GRADE METAMORPHISM

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ABSTRACT. In Celebes jadeite is an important constituent of some types of metamorphic quartzitic rocks with a blastopsammitic structure. The mineral, a chemical analysis of which is given, builds the outer parts of zoned crystals with cores of less jadeite-rich pyroxene. The mode of occurrence of the jadeite leaves no doubt concerning its metamorphic origin. The mineral often contains minute inclusions of quartz, considered to be of syngenetic origin, and has apparently been formed by conversion of original albite into jadeite and quartz. It is believed to have been produced as a stable phase, its formation evidently being due to a rather extreme local variety of low-grade regional metamorphism in the glaucophane schist facies.

It is argued that the jadeite from Burma and California may be of similar origin, and possibly also that from Japan.

The physical conditions giving rise to the formation of jadeite are evidently a special case of those producing low-grade metamorphism in the glaucophane schist facies in general. The temperatures during the production of the Celebes jadeite apparently corresponded with those during more normal types of low-grade regional metamorphism, but the confining pressures may have been comparable to those during medium-grade regional metamorphism in regions where no glaucophane has been formed. The results of the present study are compatible with one of the alternative conclusions that may be drawn from the results of recent investigations in the Geophysical Laboratory at Washington, which are based upon thermodynamic data.

INTRODUCTION

Considerable attention has been paid recently to the conditions of formation of the mineral jadeite, especially in investigations at the Geophysical Laboratory of the Carnegie Institution of Washington (Yoder, 1950; Yoder and Weir, 1951; Yoder and Chesterman, 1951; Kracek, Neuvonen, and Burley, 1951; Adams, 1953). This revival of interest in jadeite was mainly due to a theory that the mineral forms only under conditions of high pressure. The recent work in the Geophysical Laboratory was mainly based on laboratory experiments. Since all attempts to synthesize jadeite had been unsuccessful, special attention was paid to a very interesting mode of indirect thermodynamic determination of the stability range of this mineral. The different minerals involved in some hypothetical jadeite-forming reactions were investigated with respect to their heats of solution in hot hydrofluoric acid. These, mainly in combination with entropy data, permitted a rough quantitative approach of the possible conditions of formation of jadeite. Proceeding from the previous investigations in the Geophysical Laboratory, Adams (1953) calculated the stability pressure at various temperatures for the formation of jadeite from nepheline and albite. He concluded that either (1) the temperature gradient in regions where jadeite is found is lower than normal (or alternatively that the value taken for the heat of reaction should be numerically higher); or (2) jadeite has been produced in the Earth as an unstable phase and has persisted unchanged despite the insufficient pressure in comparison with the pressure required for stability. The stability pressures for the formation of jadeite and quartz from albite were also briefly considered. Here much higher values were obtained than for the other reaction, the stability pressures at 300° and 400° being respectively about 9000 and 10,800 bars.

Some years before Yoder (1950) started this series of recent papers concerning jadeite and its origin, the present author made a study of some jadeite-bearing samples collected by Brouwer's Celebes expedition, which permitted him to draw some significant conclusions concerning the origin of the Celebes jadeite (de Roever, 1947).[1] It is the purpose of the present paper to give a more elaborate discussion of the conditions of formation of the Celebes jadeite, together with new data, including a chemical analysis of the mineral. Further, a comparison is made with the main occurrences of jadeite known in other parts of the world. Since the Celebes jadeite is considered to have been formed by a rather extreme variety of low-grade regional metamorphism in the glaucophane schist facies, the conditions producing this latter type of metamorphism are also discussed. The author's conclusions on the origin of jadeite, which are based upon petrographic and field data, are compared with the recent results obtained in the Geophysical Laboratory, which are based on thermodynamic data.

MODE OF OCCURRENCE AND CHARACTERISTICS OF THE CELEBES JADEITE

During World War II, the author determined jadeite optically in two samples collected by the 1929 Celebes expedition of Prof. Dr. H. A. Brouwer, Dr. W. H. Hetzel and Dr. H. E. G. Straeter. Chemical analyses could not be made because of the difficult conditions resulting from the German occupation of the Netherlands. A rather elaborate description of both rocks, without chemical details, was published by the author in the year 1947.

Both jadeite-bearing samples were found in situ, one north of the river Salimoeroe on the trail from Majoemba to the north, approximately at 1°52′S, 120°57′E, the other in the river Koesek between Korontowoe and the Pompangeo mountains, approximately at 1°48′S, 120°59′E (de Roever, 1947, map on page 72). The distance between the two localities is about 8 km.

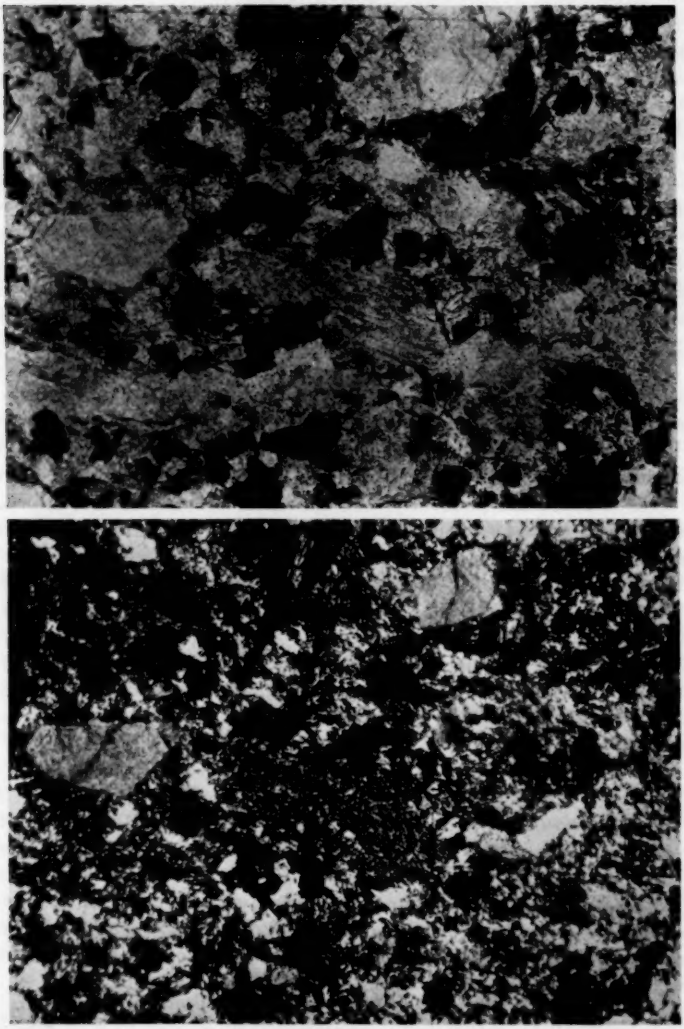
The geology of the neighboring area has not yet been studied in detail. Brouwer (1934, 1947) described complicated structures, which, according to the present author, may be due to large-scale overthrusting (de Roever, 1953). The main rock types are low-grade metamorphic clays, sandstones, conglomerates, limestones, radiolarian cherts, peridotites, spilites, and albititic rocks, with glaucophane, crossite, jadeite-bearing pyroxenes, lawsonite, and pumpellyite as characteristic metamorphic minerals. These minerals are also found as hysterogene products in medium-grade amphibolites and amphibole schists of the same area. Farther east the low-grade metamorphic rocks grade into non-metamorphic rocks. The latter are still accompanied by amphibolites and amphibole schists, but those rocks are devoid of hysterogene glaucophane, etc. (de Roever, 1947).

The jadeite-bearing sample from the river Koesek (no. 17-39) could be recognized without doubt as a blastopsammitic quartzite, with detrital crystals of quartz and small fragments of crystalline schists as well as of quartzites in a more finely crystalline matrix (pl. 1). The other (no. 16-4^{x}),

[1] The existence of this publication was unknown to Yoder when he wrote his first paper concerning jadeite (personal communication).

from near the river Salimoeroe, is also regarded as a blastopsammitic quartzite, but here the original structure is less easily recognizable.

PLATE 1



Blastopsammitic crystals of quartz (middle left and upper center) and a fragment of fine crystalline quartzite (center) are distinctly recognizable in one of the jadeite-bearing metamorphic rocks from Celebes (no. 17-39). Some of the crystals of soda-pyroxene (dark) protrude into the fragment of quartzite. Plane-polarized light and crossed nicols. × 24.

Quartz, colorless mica and jadeite-rich pyroxenes are important constituents of both rocks, and sample no. 16-4^{x} also contains large amounts of lawsonite and albite. Albite was also recognized in sample 17-39, but in smaller quantity. Subordinate constituents are chlorite, leucoxene, rutile, titanite, zircon, apatite, tourmaline, and carbonate.

In both rocks the jadeite-rich pyroxenes occur in large quantities, generally forming irregularly bounded crystals and crystal aggregates. Some of the aggregates show a divergent structure. The crystals are commonly fractured and veined. The vein-filling material is mainly quartz.

In the sample with the more distinctly recognizable structure (17-39), the crystals of pyroxene may attain about 1 mm in size. They occur as a rule in the more finely crystalline matrix. Locally they protrude into rock fragments that form distinctly bounded bodies within the matrix (pl. 1); they may also be entirely enclosed by such rock fragments. The larger, detrital crystals of quartz are locally in direct contact with the crystals of pyroxene. Smaller but still distinctly recognizable crystals of quartz are in places partly or entirely enclosed in the pyroxene. The mode of occurrence of the jadeite-rich pyroxenes leaves no doubt concerning their metamorphic origin.

The colorless mica forms some larger crystals but is mainly represented by fine scales of sericite. At least part of the sericite originated after the formation of the sediment, by metamorphic processes.

The subordinate albite is less influenced by tectonic movements than the jadeite and has an altogether fresher appearance. Moreover, these two minerals seem to occur independently. The albite, therefore, gives the impression of having been metasomatically introduced into the rock after the formation of the jadeite.

Roughly corresponding characteristics are shown by the sample 16-4^{x} (de Roever, 1947). Lawsonite, absent in the other sample, here forms numerous idioblastic crystals that are clearly of metamorphic origin. The crystals of lawsonite are sometimes crowded together and may be enclosed in the jadeite-rich pyroxene. In this sample, part of the albite occurs in sharply bounded veinlets intersecting the jadeite. Part of the quartz also occurs in veins.

In the crystals of jadeite-rich pyroxene of the sample 17-39, cores with a very strong dispersion may occasionally be observed. The pyroxene of these cores shows a very close resemblance to weakly birefringent members of the epidote-clinozoisite series. A gradual transition between rims and cores is often observed; in the sample 16-4^{x} many of the crystals of pyroxene show a zonal structure. The extreme values observed for the optical characteristics of the cores and the rims of the jadeite-rich pyroxenes in each of the samples are given in table 1. All these pyroxenes are almost or entirely colorless in thin section and show $b = n_\beta$.

TABLE 1

	Refringence	Birefringence	n_γ/c	$2V_\gamma$
16-4^{x} rims	1.66—1.67	0.013—0.014	30°—40°	72°—74½°
17-39 rims	1.67—1.68	0.012—0.013	40°—50°	70°—75°
16-4^{x} cores	— —	0.013—0.014	60°—70°	77°—85°
17-39 cores	1.69—1.71	0.014	±90°	105°—110°

The cores show yellow and abnormal blue and brownish interference colors, and their extinction n_a/c shows a very strong dispersion r>v. According to their optical characteristics, the rims especially of the crystals of soda-pyroxene in sample 16-4^x appear to represent rather pure jadeite. The rims of the crystals in the sample 17-39 are slightly different from those in the other sample, apparently mainly due to a slight admixture of acmite. The chemical composition of the cores is much more difficult to estimate, since the optical characteristics of chloromelanite and jadeite-aegirine are still almost unknown. In the paper cited (de Roever, 1947, p. 146-148) the optical properties of the cores were roughly characterized as a combination of the optical orientation of aegirine-augite or acmite and the birefringence of jadeite. In addition, they show a very strong dispersion. This combination of properties hitherto has not been described for any analyzed member of the pyroxene group. In the same paper, some arguments were given for considering that these cores may belong to the jadeite-aegirine series. Optical characteristics indicate a larger content of jadeite in both the rims and the cores of the pyroxene in sample 16-4^x than in the corresponding parts of the pyroxene crystals in sample 17-39.

Besides larger inclusions of quartz, and — in one of the samples — of lawsonite, the crystals of soda-pyroxene rather commonly contain smaller though still recognizable inclusions of sericite in fine scales, and of leucoxene (probably mostly rutile). Further, the outer parts of the jadeite-rich rims of the pyroxene crystals in sample 17-39 are often turbid from the presence of minute inclusions that could not be identified with the aid of the microscope. These inclusions, with an average size of less than 5 microns, show a much lower refringence than the soda-pyroxene, while the birefringence in some of the larger inclusions is weak. In sample 16-4^x the greater part of each crystal is commonly turbid, the crystals here being richer in jadeite than those in the other rock. Evidently, this turbid appearance is especially characteristic for the most jadeite-rich pyroxenes. A mixture of clear and turbid jadeite-rich pyroxene from sample 17-39 — the concentrate used for the analysis given below — was investigated by Dr. Hatten S. Yoder with the aid of the Norelco Geiger-counter X-ray spectrometer of the Geophysical Laboratory of the Carnegie Institution of Washington. The powder X-ray diffraction record of the Celebes jadeite was compared with that of jadeite from Burma and appeared to show extra peaks, coinciding exactly with the main peaks of quartz. Judging from the relative intensities, Dr. Yoder would estimate that there is approximately 5 percent of quartz in the concentrate of the Celebes jadeite. Evidently the minute inclusions in the jadeite-rich pyroxenes consist of quartz.

As mentioned above, no chemical analyses could be made during the preparation of the author's first description of these rocks. By courtesy of Professor C. E. Tilley of the University of Cambridge, who was interested in the chemical composition of these pyroxenes and who had an analysis made in his laboratory, the author is now able to give chemical data on the Celebes jadeite, which confirm the optical determination of this mineral.

The mineral separation was performed at the Geological Institute of the

University of Amsterdam. According to their optical characteristics the rims of the pyroxene crystals of sample 16-4^{x} are richer in jadeite than those of sample 17-39. Since sample 16-4^{x} was smaller, however, and since the pyroxene of this sample is more turbid than that of sample 17-39, the mineral separation was performed on the latter sample, notwithstanding the less jadeite-rich character of its pyroxene. Since most pyroxene crystals in this sample show intergrowths of clear and turbid parts, very fine fractions were used for the ultimate separation. Even then, however, it was impossible to obtain an adequately large concentrate of the clear pyroxene of the rims. Therefore, the analysis had to be made on material containing a considerable amount of turbid pyroxene with inclusions of quartz. The ultimate specific gravity separation was performed with the aid of mixtures of methylene iodide and acetylene tetrabromide. A concentrate of specific gravity 3.26-3.30, after tedious hand-picking, gave slightly more than 3 grams of material for the analysis and further investigations. This material was practically pure except for the quartz-inclusions in the turbid crystal fragments. According to an estimate on 500 crystal fragments the amount of rim-pyroxene together with admixed quartz is approximately 97½ percent. The remainder consists mainly of core-pyroxene, the amount of which in view of its similar chemical composition is sufficiently small to be neglected. There is also a very small percentage (one fragment in 500) of rutile.

The results of the analysis of the jadeite-concentrate of sample 17-39 by Mr. J. H. Scoon of the University of Cambridge are given in the accompanying table 2.

TABLE 2

	I	II	III		IV		V		VI	
SiO_2	60.50	58.51	59.51	Si	2.049		2.000		2.008	
Al_2O_3	20.87	22.00	24.31	Al	.833		.886		.963	
Fe_2O_3	3.14	3.31	.35	Fe‴	.081		.086		.008	
FeO	.93	.98	.03	Fe″	.026	.975	.029	1.027	—	1.000
MgO	.47	.50	.58	Mg	.024		.026		.029	
TiO_2	.44	—	.01	Ti	.011		—		—	
CaO	.67	.71	.77	Ca	.024		.027		.028	
Na_2O	13.03	13.74	14.37	Na	.854	.890	.911	.950	.939	.967
K_2O	.25	.26	.02	K	.012		.012		—	
H_2O+	.15	—	.06							
H_2O-	.08	—	—							
Cr_2O_3	n.d.	—	.01							
MnO	tr.	tr.	.01							
	100.53	100.01	100.03							

I. Jadeite with minute inclusions of quartz and a very small amount of admixed rutile, S. Koesek between Korontowoe and the Pompangeo mountains, eastern central Celebes. Analysis by J. H. Scoon.

II. Analysis I after subtraction of TiO_2, H_2O and 5% of quartz recalculated to 100%.

III. Jadeite, Burma. Analysis by E. G. Zies (Yoder, 1950).

IV. Number of atoms in I (after subtraction of H_2O) on the basis of 6 oxygens.

V. Number of atoms in II on the basis of 6 oxygens.

VI. Number of atoms in III on the basis of 6 oxygens.

Since the analyzed jadeite-concentrate contained a considerable amount of impurities, especially in the turbid parts of the crystal fragments, the analysis was recalculated. The amount of enclosed quartz was assumed to be 5 percent, according to Dr. Yoder's rough estimate based on the powder X-ray diffraction record. Judging from the atomic ratio Si:O for the recalculated analysis, this estimate seems to be surprisingly exact. Further, all TiO_2 present was considered to represent admixed rutile, while H_2O was omitted since its constituents probably do not enter the pyroxene structure (see Hess, 1949). The small contents of K_2O and H_2O^+ may be due to the presence of some admixed sericite, the only other mineral that was observed as inclusions in the pyroxene of sample 17-39. This mineral, however, was not subtracted during the recalculation, since it was not observed in the concentrate itself.

The recalculated analysis given in the table, which may be compared with that of jadeite from Burma by E. G. Zies, was worked out to a pyroxene formula with fairly satisfactory results. The conclusion may be drawn that the weight percentage of jadeite in the analyzed pyroxene is larger than 80 percent. Therefore, according to the suggestion of Washington and Merwin (1927) concerning the nomenclature of pyroxenes, this mineral may be designated as jadeite. Moreover, the content of acmite appears to be larger than that of diopside and hedenbergite, again as indicated by the optical characteristics.

GENESIS OF THE CELEBES JADEITE

The mode of occurrence of the Celebes jadeite in metamorphic sedimentary rocks leaves no doubt concerning its metamorphic origin.

From a theoretical point of view jadeite could conceivably be formed by various different reactions. According to the more important of these reactions the original material giving rise to the formation of jadeite during metamorphism may have been either analcite, or nepheline and albite, or albite alone. Neither analcite nor nepheline, however, is known to occur in the less metamorphosed or non-metamorphic rocks of the region under consideration. Further, the mode of occurrence of the Celebes jadeite as a metamorphic mineral in original psammitic rocks forms an even more important argument against its formation at the expense of original analcite or of a mixture of nepheline and albite. On the contrary, this mode of occurrence indicates that the Celebes jadeite has been formed by conversion of albite, which is a normal constituent of many psammitic rocks. Both jadeite-bearing rocks, therefore, are to be considered as metamorphic arkoses, in which the jadeite has been formed according to the reaction:

$$\text{albite} = \text{jadeite} + \text{quartz}$$

Again, the Celebes jadeite contains a rather large quantity of minute inclusions of quartz. These inclusions appear to occur especially in the most jadeite-rich parts of the pyroxene crystals. They are much smaller than the crystals of quartz in the surrounding matrix, which already possessed their present dimensions at the time of the main phase of metamorphism, i.e. during the crystallization of the jadeite. Therefore, the minute inclusions of quartz within the jadeite are not considered as representing undigested or undis-

placed material of the matrix, but as being of syngenetic origin with the jadeite. This conclusion seems also warranted in view of the intricate intergrowth of these minerals. It is clear that a syngenetic product consisting of jadeite and quartz could only have been formed at the expense of albite, by the reaction mentioned above.

It may be remarked that the amount of enclosed quartz occurring in the analyzed concentrate is considerably smaller than the molecular equivalent of the amount of jadeite, since there is much jadeite without inclusions. Part of the quartz formed has apparently not been enclosed by the soda-pyroxene.

The joint occurrence of jadeite, albite and quartz in both jadeite-bearing samples deserves some special attention, for in this assemblage the number of minerals is larger than the number of individual components (e.g. $NaAlSi_2O_6$ and SiO_2), in contradiction to the requirement of Goldschmidt's mineralogical phase rule for normal equilibrium assemblages. As noted above, the albite found in both samples gives the impression of having been introduced into the rocks after the formation of the jadeite. Therefore, the observed albite is not considered as a remainder of the original albite of the arkoses, which evidently has been entirely transformed into jadeitic pyroxene and quartz. During a later stage in the history of the rocks, after the main phase of metamorphism, a renewed change of the physical conditions allowed the crystallization of the younger albite. During this later phase, however, the jadeite was not altered but persisted as an unstable relic. The jadeite, albite and quartz of the rocks in question therefore represent a disequilibrium assemblage.

The type of metamorphism causing the production of the Celebes jadeite is best studied by making a comparison with the metamorphism in the neighboring part of the island of Celebes (de Roever, 1947, 1950, 1953). The region around the jadeite localities has mainly been affected by two types of metamorphism, of different age: (1) an older regional metamorphism in the epidote-amphibolite facies, which is older than the Alpine orogenetic cycle; and (2) a younger regional metamorphism, of Alpine age, in the lawsonite-glaucophanite subfacies of the glaucophane schist facies.[2] There are several arguments indicating that the jadeite-bearing rocks have not been affected by the older metamorphism, but that they were mainly metamorphosed under conditions producing the mineral paragenesis of the glaucophane schist facies. Firstly, epidote, green or blue-green amphibole and garnet, which are characteristic for the older metamorphism of the surrounding region, have not been found in the jadeite-bearing rocks, whereas one of these contains lawsonite, a critical mineral of the glaucophane schist facies. Further, many of the rocks in the surrounding parts of eastern central Celebes that have not been affected by the older metamorphism in the epidote-amphibolite facies, but that were mainly influenced by the younger metamorphism in the glaucophane schist facies, are more or less rich in pyroxenes, which — according to their optical characteristics — have a rather large content of jadeite.

[2] The existence of an independent glaucophane schist facies as assumed by Eskola (1929) is now definitely established (de Roever, 1950, 1955; Brouwer and Egeler, 1952; Routhier, 1953).

Therefore, these pyroxenes are considered as belonging to the mineral paragenesis of the glaucophane schist facies. These jadeite-bearing pyroxenes occurring in other rocks of the glaucophane schist facies sometimes show a zonal structure, with rims that are richer and cores that are poorer in jadeite. It was already mentioned that the same holds good for the pyroxene of the jadeite-bearing samples 17-39 and 16-4[x] described in this paper. A comparable zonal structure is also shown by a number of soda-amphiboles of this region, with rims that are richer in glaucophane and cores that are richer in crossite. In both soda-amphiboles and soda-pyroxenes the rims are poorer and the cores are richer in iron. The widespread occurrence of jadeite-bearing pyroxenes in rocks of the glaucophane schist facies is not confined to Celebes but has also been described for several other regions, e.g., Greece (Ktenas, 1907) and Corsica (Brouwer and Egeler, 1951, 1952; Netelbeek, 1951). This widespread occurrence of jadeite-bearing pyroxenes indicates that the Celebes jadeite has not been formed by some special type of local metamorphism but by a local variety of regional metamorphism. The metamorphism producing the Celebes jadeite, however, has to be considered as a rather extreme case of regional metamorphism in the glaucophane schist facies, since the soda-pyroxene here is especially rich in jadeite. It may be remarked that the term "glaucophane schist facies" is used here in a rather broad sense, since the soda-amphibole may not be represented by glaucophane but by related minerals, such as crossite or the rare members of the amphibole group occurring at the jadeite localities of Burma, which are mentioned below.

In many regions large quantities of pyroxenes with a considerable content of jadeite have been formed at the expense of widely different material in both original igneous and original sedimentary rocks. Probably, therefore, neither these pyroxenes nor jadeite itself have been produced as unstable phases. Furthermore, in the great majority of the rocks studied by the present author the crystallization of the jadeite-bearing pyroxenes does not seem to represent a transitional stage in the formation of other metamorphic minerals, and jadeite itself obviously does not represent such a transitional stage. The Celebes jadeite, therefore, is believed to have been produced as a stable phase.

There are several indications that the metamorphism in the glaucophane schist facies producing the Celebes jadeite was a low-grade metamorphism. One of these is found in the good preservation of the blastopsammitic structure shown by the jadeite-bearing sample 17-39. Further, in eastern central Celebes all transitions have been found between non-metamorphic rocks and rocks affected by the metamorphism in the lawsonite-glaucophanite subfacies of the glaucophane schist facies. Moreover, the absence of garnet in the mineral paragenesis of the glaucophane schist facies around the jadeite localities indicates that here the metamorphism is of a lower grade than that of the garnet-lawsonite-glaucophane schist subfacies and that of a possible subfacies with garnet and epidote. The former has been recognized in the southern part of South East Celebes and is apparently to be considered as the adjoining higher metamorphic equivalent of the lawsonite-glaucophanite subfacies, while the latter seems to occur in the northern part of South East Celebes (de Roever, 1947, p. 168-169) and also in northern Corsica (Egeler, 1948).

Summarizing, the jadeite of eastern central Celebes is to be considered as having been formed at the expense of original albite by a rather extreme local variety of low-grade regional metamorphism in the glaucophane schist facies.

COMPARISON WITH OTHER OCCURRENCES OF JADEITE

Moderately pure to almost completely pure jadeite is known to occur in situ in three other regions: Burma, Japan and California. In these regions the jadeite is mainly found in bodies that are surrounded by serpentine. The best-known example, that of Burma, will be more elaborately discussed here. The jadeite localities of Japan and California, which were discovered not long ago and therefore have not been subjected to much detailed investigation, will be more briefly dealt with. A summarizing description of the jadeite deposits of Burma and Japan was recently given by Yoder (1950), and the California jadeite has mainly been studied by Yoder and Chesterman (1951). More complete references may be found in the papers mentioned.

The Burma jadeite occurs mainly in close association with albite and with some peculiar types of amphibole, such as Krenner's széchenyiite (1899)[3] and the széchenyiite-like amphibole described by Lacroix (1930). These amphiboles belong to the richterite- and eckermannite-types, respectively, of Sundius' classification of the amphiboles (1946), with the simplified formulas $Na_2CaMg_5(OH)_2Si_8O_{22}$ and $Na_3Mg_4Al(OH)_2Si_8O_{22}$. They are rich in soda and magnesia and therefore are rather closely related to glaucophane. In the best known non-detrital occurrence of jadeite in Burma, that of Tawmaw, these amphiboles are mainly found in zones adjoining the surrounding ultrabasic rocks.

The most recent opinions on the genesis of the Burma jadeite that are based on petrographic or field evidence (Lacroix, 1930; Chhibber, 1934) favor direct crystallization from a desilicated granitic magma under high confining pressure. The peculiar composition of the amphibole-rich rocks was explained by interaction of soda-rich invading material with the magnesia-rich country rock. The considerable enrichment in silica involved in the transformation of the original peridotite into the amphibole-rich rocks was supposed to indicate that the invading material was not undersaturated. Nepheline, it is true, was found by Bauer (1896) in some jadeite-bearing samples said to come from Tibet but presumably originating in Burma.[4] As stated by Lacroix, however, this nepheline is not of primary origin, for it occurs in veins as well as in poikilitic crystals surrounding corroded fragments of larger jadeite crystals. Both Lacroix and Chhibber supposed that the composition of the invading material was that of a "soda-granite-aplite." This aplitic magma was believed to have been derived from granites occurring in the same area.

As to whether the Burma jadeite crystallized directly from the invading material or was produced by metamorphism, the literature shows rather much divergence of opinion. Neither Lacroix nor Chhibber gave any arguments

[3] Krenner gave the name széchenyiite, after Count Béla Széchenyi, and not széchenyite, as written by Lacroix.
[4] See Yoder (1950).

of importance against a metamorphic production of the jadeite at the expense of original material that was not undersaturated, for previous authors favoring a metamorphic origin of the jadeite had assumed the original material to be a nepheline-bearing rock. But it is now established that jadeite can be produced as a metamorphic mineral, at the expense of original albite, whereas its occurrence as a product of direct igneous crystallization has never been proved. On the contrary, according to the present author, several peculiarities shown by the deposits of Burma seem to find a better explanation by assuming a metamorphic origin of the jadeite. Such are, for instance, the schistosity as well as the banded character of several samples, e.g. some of those studied by Bauer (1906) and Bleeck (1907), and also the conspicuous cataclastic phenomena shown by numerous jadeite-bearing rocks and described by many authors, for these cataclastic phenomena cannot be ascribed only to movements subsequent to the crystallization of the jadeite. In one of the samples studied by Lacroix, for instance, large crystals of amphibole that enclose some large crystals of jadeite and that are bent and broken are traversed in all directions by cracks containing small crystals of younger jadeite (Lacroix, 1930, p. 242).

Furthermore, according to Chhibber, glaucophane schists, partly considered as metamorphic gabbros, are quite common in the area. Chhibber remarked: "In view of the presence of jadeite-bearing rocks in the neighbourhood, these glaucophane schists are significant, as glaucophane contains the jadeite molecule." He did not pursue this trend of thought in his further conclusions, however.

Lacroix and Chhibber call the original material a "soda-granite-aplite," but quartz-rich vein rocks with albite as the main constituent and the only feldspar can better be designated with the term quartz-albitite, in view of the absence of potash-rich feldspar (de Roever, 1940). The comparatively large percentage of jadeite present in the rocks in question seems to indicate, however, that the original material contained little or no free quartz, and therefore was an albitite.

According to the above arguments the author would suggest that the Burma jadeite, like that from Celebes, formed at the expense of original albite by a rather extreme local variety of regional metamorphism in the glaucophane schist facies. In Burma, however, the liberated silica apparently reacted with material derived from the neighboring ultrabasic rocks, giving rise to széchenyiite and széchenyiite-like amphiboles. The absence of schistosity in most of the rocks compares with its absence in many low-grade metamorphic rocks of the glaucophane schist facies.

As elsewhere both albitites and quartz-albitites are commonly found to be genetically related to ophiolitic rocks, the same may hold good for the original material of the jadeite deposits of Burma.

In accordance with well-known laboratory experiments, the nepheline studied by Bauer and Lacroix may possibly have been formed by a later thermal metamorphism of the jadeite, which in Burma can be easily accounted for.

Jadeite was first discovered in Japan in 1938. According to Iwao (1953) and according to Yoder's quotations from articles published in Japanese as well as from an unpublished report, this occurrence is very similar to the Burmese deposits. In Japan, however, the jadeite is said to be mainly accompanied by albite, quartz and actinolite. In a typical occurrence, the amphibole is found in zones adjoining the surrounding serpentine, like the soda-amphibole of the jadeite deposit of Tawmaw in Burma. According to the descriptions available to the author, the optical characteristics of széchenyiite and the széchenyiite-like amphibole from Burma seem to show a close resemblance to those of actinolite. Therefore the amphibole of the Japanese jadeite locality may also contain a large amount of soda, and consequently be near to glaucophane in composition. Glaucophane has not been found in the neighboring area, but the jadeite occurs in a body of serpentine that seems to belong in the same belt as many occurrences of glaucophane in southwestern Japan.

The jadeite-bearing rocks from California, according to the preliminary description of Yoder and Chesterman (1951), commonly have a banded appearance. In one of the lens-like bodies there is evidence that green jadeite was crushed and sheared into a flaser structure before the crystallization of white jadeite. The jadeite may be associated with lawsonite or glaucophane, among other minerals. These data strongly suggest that the California jadeite has also been formed by metamorphism in the glaucophane schist facies.

GEOLOGICAL INDICATIONS CONCERNING THE CONDITIONS OF FORMATION OF JADEITE

The conclusions reached in a preceding paragraph are considered to indicate that the combination of physical factors producing jadeite in metamorphism represents a rather extreme variety of that producing low-grade metamorphic rocks of the glaucophane schist facies. Therefore, the physical conditions that give rise to low-grade glaucophanitic metamorphism in general may first be discussed (see also de Roever, 1950, 1955).

Low-grade metamorphic rocks of the glaucophane schist facies may be either of regional occurrence or of irregular distribution amidst non-metamorphic rocks, and they may show gradual transitions into these latter rocks. Their mode of occurrence shows a rather close resemblance to that of rocks of the green schist facies. Evidently, the physical conditions giving rise to these two types of metamorphism are not widely different. Glaucophane schists, however, are relatively dense rocks compared with green schists of like chemical composition. As already recognized by Eskola (1929), this is one of our main clues concerning the physical conditions giving rise to metamorphism in the glaucophane schist facies. Since there seems to be no reason to assume that the temperatures during low-grade metamorphism in this facies differed markedly from the temperatures during metamorphism in the green schist facies, this relatively high density is considered to indicate that low-grade metamorphic rocks of the glaucophane schist facies, compared with rocks of the green schist facies, have been formed under higher confining pressures. This conclusion, however, does not imply that these confining pressures were much higher, or, in other words, that the differences in

confining pressure concerned were of great magnitude; the contrary is indicated by the mode of occurrence of the metamorphism in question. A relatively small difference in confining pressure may have been sufficient to produce the mineral paragenesis of the glaucophane schist facies instead of that of the green schist facies, not much more perhaps than the very small change in confining pressure sufficient to cross the boundary between the adjoining fields of stability of a lower and a higher pressure mineral. Thus the difference in confining pressure in question cannot be inferred from the field relations of low-grade glaucophanitic rocks and green schists.

The role of shearing stress during metamorphism in the glaucophane schist facies does not seem to have been markedly different from that during metamorphism in the green schist facies.

Summarizing, the physical conditions giving rise to low-grade metamorphism in the glaucophane schist facies, as compared with those producing metamorphism in the green schist facies, are considered to be especially characterized by somewhat higher confining pressures. The temperature and the magnitude of the shearing stress during each of these types of metamorphism do not seem to have been essentially different.

As described on a preceding page, the pyroxene of the jadeite-bearing samples as well as some other soda-pyroxenes from Celebes show a zonal structure, with rims that are richer and cores that are poorer in jadeite. This type of zoning is comparable to that most frequently shown by the soda-amphiboles of this region, with rims that are richer in glaucophane and cores that are richer in crossite. This zonal structure is thought to reflect a gradual development of the crystals during progressive metamorphism in the glaucophane schist facies, i.e. the glaucophane is considered to have been formed by a slightly higher grade of metamorphism than the crossite, and the jadeite than the less jadeite-rich pyroxenes. It may be pointed out, however, that — in contrast to the jadeite described in this paper — part of the glaucophane found in Celebes has been formed by medium-grade metamorphism, together with garnet.

Since the jadeite is not believed to have been produced as an unstable phase, as argued on a preceding page, and since there seems to have been sufficient albite in many of the rocks in question, the rare occurrence of the jadeite compared with the other soda-pyroxenes and soda-amphiboles mentioned may be explained by assuming that the combination of physical conditions necessary for the conversion of albite into jadeite and quartz was exceptional. According to the data given above, however, it was not the grade of metamorphism during the formation of the jadeite that was exceptional. Therefore, the mutual relation of the separate physical factors during the conversion of albite into jadeite and quartz is considered to have been abnormal. In view of the large reduction in molecular volume accompanying this reaction, it is apparently the comparative importance of the pressure factor that has been exceptional; i.e., greater than during normal low-grade metamorphism in the glaucophane schist facies, in which the confining pressures were already somewhat higher than those during metamorphism in the green schist facies. Nevertheless, the confining pressures during the produc-

tion of the Celebes jadeite at the expense of original albite — like those during low-grade glaucophanitic metamorphism in general — do not seem to have been of very great magnitude, as suggested by considerations based on the low-grade character of the metamorphism in and around the jadeite localities as well as on the general geological setting of the neighboring area.

Summarizing, the temperatures during the production of the Celebes jadeite by conversion of original albite into jadeite and quartz apparently corresponded with those during more normal types of low-grade regional metamorphism, but the confining pressures necessary for this conversion may have been comparable to those during medium-grade regional metamorphism in regions where no glaucophane has been formed.

Roughly similar conditions may have governed the formation of the jadeite in the other regions where this mineral has been found in place. Here, however, at least part of the SiO_2 produced during the conversion of the original albite appears to have reacted with other minerals.

COMPARISON OF THE RESULTS OBTAINED WITH THOSE OF RECENT INVESTIGATIONS IN THE GEOPHYSICAL LABORATORY, WASHINGTON

The results of recent investigations on jadeite in the Geophysical Laboratory of the Carnegie Institution of Washington are mentioned in the introduction of this paper.

According to the conclusions drawn in the present study, at least part of all jadeite known has been formed by metamorphic reactions. The formation of jadeite at the expense of original nepheline and albite — the stability relations of which were elaborately discussed by Adams (1953) — does not seem to have taken place in nature. This may be explained by the general absence of nepheline in the original material of rocks of the glaucophane schist facies.

The Celebes jadeite has been formed by the conversion of albite into jadeite and quartz, which, according to the results obtained in the Geophysical Laboratory, requires considerably higher confining pressures. The stability relations of this conversion were briefly discussed by Adams. The stability pressures at 300° and 400°C. were given to be respectively about 9000 and 10,800 bars. According to the results mentioned above, however, the natural formation of jadeite may have occurred at lower temperatures, possibly nearer to 200°C. For this temperature the stability pressure, calculated in a similar way, would be roughly 7000 bars, i.e. a value higher than that to be expected for the formation of the jadeite found in nature. It must be pointed out, however, that this figure is based partly on averages for the heats of solution of albite and jadeite in hot hydrofluoric acid, and that the two separate values obtained for the heat of solution of albite, especially, show a rather large difference, corresponding to a difference of 4000 bars in the stability pressure concerned. In view of the great magnitude of this difference, one of the two separate values obtained for the heat of solution of albite does not seem a sufficiently reliable base for the calculation of the stability pressure in question. Therefore, the stability pressure at 200°C. for the conversion of albite into jadeite and quartz, instead of approximately corresponding to the average

value of 7000 bars, may be much nearer to either 9000 or 5000 bars. The uncertainty of each of these values, however, is still considerable. Thus, the results obtained in the Geophysical Laboratory may suggest either (1) that the jadeite found in nature has been produced as an unstable phase; or (2) that it has been produced as a stable phase, under comparatively low temperatures and comparatively high pressures. The latter alternative is entirely compatible with the conclusion in the preceding section that the temperatures during the production of the Celebes jadeite were apparently about those during more normal types of low-grade regional metamorphism, but that the confining pressures may have been comparable to those during medium-grade regional metamorphism in regions where no glaucophane has been formed.

In view of recent estimates of the magnitude of the physical variables during regional metamorphism (Turner and Verhoogen, 1951) the confining pressures during the formation of the jadeite may have been considerably lower than 5000 bars, perhaps between 3000 and 4000 bars. Such pressures, however, may still be within the uncertainty of the lowermost stability pressures that can be calculated from separate values for the heats of solution of albite, jadeite, and quartz.

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PETROFABRICS AND CLASSICAL ARCHEOLOGY

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ABSTRACT. Petrofabrics is applied to two problems of classical archeology: determining provenance of building and statuary marble, and assembling inscriptions. Parian lychnites marble is found to have a weakly oriented fabric, Naxian and Delian marble a very strongly oriented fabric with one great maximum. Pentelic and Hymettian marble also have distinctive fabric patterns. Fabric work on inscription fragments indicates that differing patterns are from different inscriptions, but similar patterns may indicate only a contemporaneous origin for separate inscriptions.

INTRODUCTION

This paper is not a contribution to the basic data of petrofabrics, but rather a diverting application of petrofabric methods to two typical problems of classical archeology. The prime problem concerns itself with the origin of different statuary and building marble. The second problem has to do with assembling inscription fragments.

Archeologists have long known that marble was quarried in ancient Greece at certain sites and at definite times. They know that most of the early marble came from the island of Naxos; later a beautiful translucent variety was discovered and mined on the island of Paros, and called lychnites, from λύχνος, lamp, because lamps were used in the underground workings. Finally, during the golden age of Athens, marble was discovered on Mount Pentelikon, in Attica, which supplanted island marbles as a building stone. Since all varieties were selectively quarried with the same standard in mind, that is, purity of color, they are difficult to tell apart. In fact, no simple petrographic method has yielded definitive criteria for any one marble. Petrofabrics was tried in the hope that each marble might prove to have a distinctive fabric.

An interesting digression from this main problem was furnished by an epigrapher, W. K. Pritchett, who was trying to assemble fragments of different inscriptions. His first problem was deciding which fragments belonged together, before he could start assembling the separate inscriptions. His quandary is similar to the family's at Christmas, doing jig-saw puzzles after Junior has mixed several sets together. Petrofabrics was used to see if the different inscriptions had distinctive, or differently oriented fabrics; if so, then important pieces could be assigned on the basis of their own particular fabric.

The opportunity for this study was provided by the Fulbright Act, during 1951-1952, when the author was a Research Scholar in Geology in Greece.

The author is expressly indebted to Professor Ernst Cloos for first suggesting to him that classical archeo-geology might prove to be an interesting research, and for his unflagging interest in the author's own progress in the field. Assistance and encouragement should also be acknowledged from Professors H. W. Fairbairn, A. N. Georgiades, Bruno Sander, H. A. Thompson, and Francis J. Turner. Professor Fairbairn also kindly read and criticized the manuscript. The author's wife, Rhoda Herz, drafted figure 2.

PROCEDURE

Oriented specimens were collected from ancient quarries on the islands of Naxos, Paros, and Delos in the Cyclades, and from Mounts Pentelikon and Hymettus in Attica for the primary study (fig. 1). To assist the epigrapher, pieces were cut from the back side of inscription fragments, then wafers for thin sectioning were sawed from these pieces perpendicular to the inscription face and parallel to the inscribed lines. On the finished inscription thin sections a barbed arrow pointed to the left margin, and the barb to the top. Oriented thin sections were also prepared from the quarry samples.

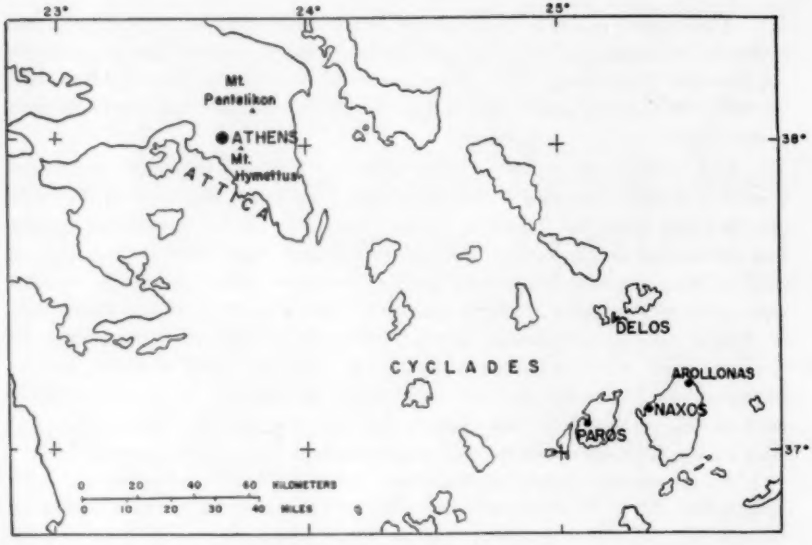

FIGURE 1. INDEX MAP.

The fabric diagrams were prepared at the Mineralogische-Petrographische Institut in Innsbruck and at the mineralogy laboratories of the University and the Greek Geological Service in Athens. Poles to $(01\bar{1}2)$ composition planes were plotted for each thin section; the total number of plotted poles varied from 150 for an inscription to 400 for the Parian marble.

ATTIC MARBLES[1]

Pentelic marble.—The type locality for the classical Pentelic marble is the ancient quarry of Spilia Daveli on the southern slope of Mount Pentelikon. Five gradational types of marble are found:

(1) marble breccias, best developed near the base of the mountain,
(2) schistose marbles, found especially about the schist-marble contacts,
(3) white, medium-coarse-grained marbles, aesthetically "Pentelic," and the Pentelic marble of this study,

[1] These next two sections are abridged from Herz, 1951, p. 16-28.

(4) banded blue and white, or medium- and coarse-grained marble, aesthetically "Hymettian," and

(5) dolomitic marble, finer grained than any of the others.

Type (3), white marble, was selectively quarried in antiquity, and is also the "Pentelic marble" of most archeological descriptions. It is typically well foliated, the plane of foliation indicated by muscovite or chlorite. Grain size may also vary in bands parallel to the folia, coarse grains measuring 0.6 by 0.8 mm alternating with fine to medium grains. Quartz, graphite, and magnetite or pyrite may occur in minor amounts.

Hymettian marble.—The type locality for the classical Hymettian marble is about the lower reaches of the Kakorhevma on the western slope of Mount Hymettus, in an area of old Roman quarries. The same general marble types are found here as on Mount Pentelikon, though the banded marbles (4), "Hymettian marble" of most archeologists, dominate in the quarries. These rocks tend to be finer grained than the Pentelic and are not very translucent. The best Pentelic is translucent through a 15 mm diameter, Hymettian through only 5 mm (Lepsius, 1890, p. 47). The color banding is apparently due to abundant included carbonaceous material in certain bands. For more on the Hymettus-Pentelikon relations, see Herz and Pritchett, 1953, p. 73-76.

ISLAND MARBLES

Introduction.—Most marbles from the Cyclades Islands are coarse to very coarse to granular and lack a well-defined foliation plane. These two criteria are the best for differentiating island from Attic marbles, although they are not infallible. Thus, Parian lychnites marble may be about equigranular to Pentelic, but is much more translucent. Accessory minerals, abundant in Attic marbles, are generally not as common in the island varieties.

Parian marble.—Most of the marble quarried on the island of Paros was obtained in the valley of the present-day Aghias Minas, about 5 kilometers east of the town of Paros. The lychnites marble was mined in a bed that is only 3 meters thick and dips to the east 35°, an extremely steep slope for primitive mining operations. The rock is a remarkably pure crystalline calcite marble. Accessory minerals are not seen, and the calcite grains themselves have rather uniform dimensions. Most of the grains are about 1 to 2 mm in diameter, though many range down to about ½ mm, about the dimensions of Pentelic marble; the Parian marble lacks a well-defined foliation, however. The lychnites marble is translucent through a thickness of about 35 mm (Lepsius, 1890, p. 47) and was the most popular statuary marble of Greek antiquity because of its high translucency and purity, and the fact that it could be worked comparatively easily. There was little danger of a nearly finished work splitting on a well-developed foliation plane, nor of a cluster of splotchy black magnetite crystals coming to light in a prominent area.

Other Parian marble was quarried on the west side of the same valley of Aghias Minas and in another valley, a little over 3 kilometers east of the town of Paros. These types are similar in hand specimen to Naxian marble.

Naxian marble.—Most of the ancient workings of Naxos were on the northeast coast of the island, to the west of and about the town of Apollonas.

This marble lacks a well-defined foliation plane, is coarse to granular, and commonly shows dark gray bands of included carbonaceous matter in the otherwise white marble. The volume of accessory minerals is highly variable; muscovite, quartz, and graphite are normally present, and biotite, hornblende, magnetite, and lime silicates including grossularite occur where the marble is interbanded with gneiss. The Naxian marble is not nearly as translucent as the lychnites.

Delian marble.—Marble was quarried in small pits on the island of Delos and may have been used locally. It is generally indistinguishable from the Naxian marble in hand specimen.

FABRIC OF THE QUARRY MARBLES

Preliminary fabric work shows promising results. The diagrams presented here are not offered as final, but rather as suggestive of the lines that future work should follow.

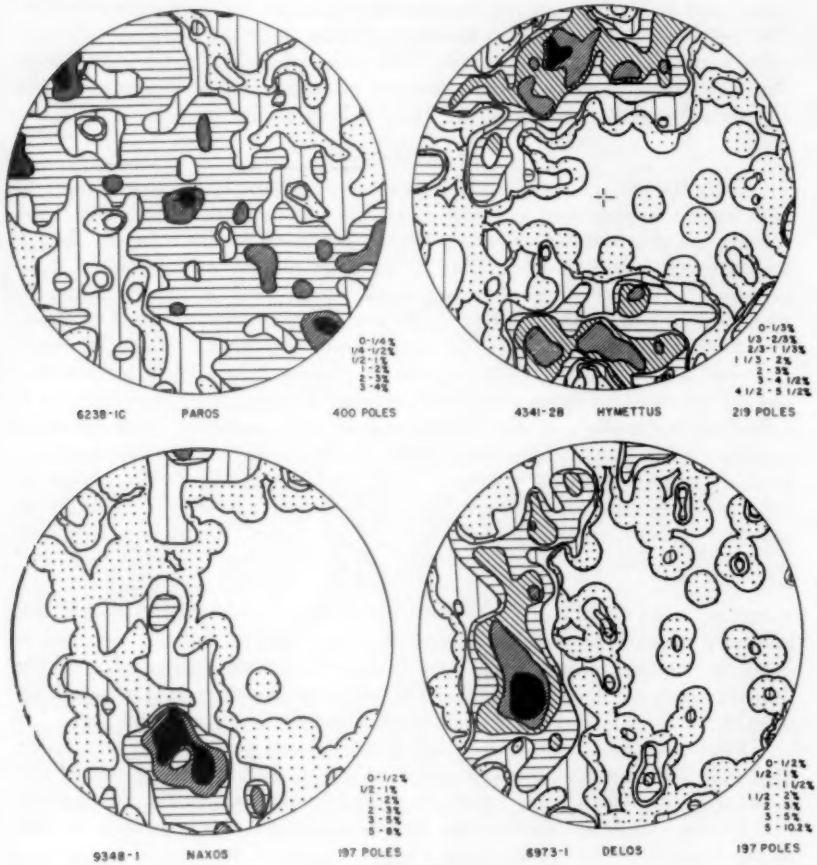

Fig. 2

Parian lychnites marble (fig. 2, 6238-1C) has a fabric that is weakly oriented, in a broad girdle pattern with only two maxima. The thin sections show an excellent foliation formed by rectangular calcite grains, in bands, with a definite though slight elongation to them. The larger grains, averaging 1.6 by 1.3 mm, tend to a rectangular shape; the smaller, averaging 0.40 by 0.35 mm, are more sutured. Very fine disseminated carbonaceous matter is seen throughout the slides.

Naxos Apollanas marble (fig. 2, 9348-1) yields a very strongly oriented fabric in a narrower girdle, and with only one very great maximum. In thin section it shows no apparent foliation, and grains vary from very coarse, 3.0 by 2.0 mm to fine, 0.6 by 0.3 mm. Abuandant opaques, such as limonite and pyrite, comprise the accessories.

The Delian marble, (fig. 2, 6973-1) has a fabric that is similar to the Maxian marble. It is also similar in thin section.

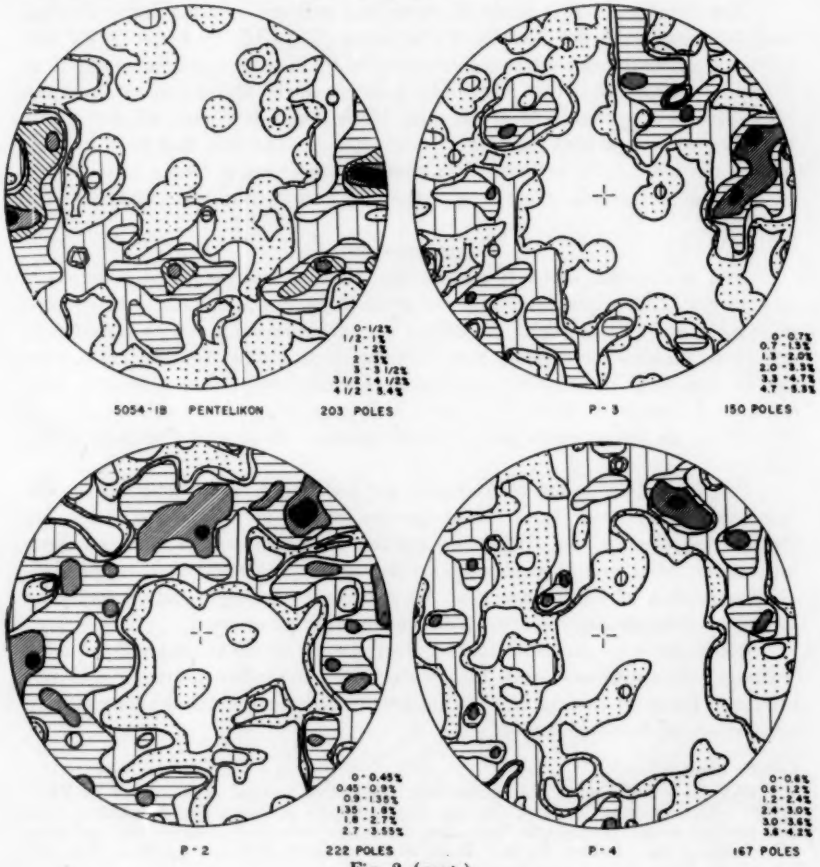

Fig. 2 (cont.)

Pentelic Spilia marble (fig. 2, 5054-1B) yields a fabric with a very strong incomplete girdle, and with several maxima, very different from any of the island marbles. The thin section shows grains varying from about 0.70 by 0.60 mm to 0.35 by 0.25 mm. Carbonaceous matter is abundant; muscovite and quartz are also present.

Hymettian Kakorhevma marble (fig. 2, 4341-2B) shows a strongly oriented fabric in a weak girdle and with one or two maxima. In thin section it is fine to medium grained and layered, with fine-grained graphite-rich bands or alternating fine- and medium-grained bands.

FABRIC OF THE INSCRIPTIONS

As a test of the method, three thin sections were studied, two belonging to one inscription and a third to another. It was known that both inscriptions were made about the same time, so it was possible that both slabs were quarried about the same time.

The resulting fabric from all three thin sections is remarkably similar, and also similar to the Pentelic Spilia fabric, 5054-1B. In figure 2, P2 and P3 are fragments from the same inscription; P4 is from a second inscription. A logical conclusion is that both slabs were cut in the Spilia quarry about the same time, and probably from the same block. Then they were shipped to the inscriber who preserved the quarry's orientation. The fact that both inscriptions have identically oriented fabrics almost suggests a "mass production" of slabs in the ancient quarry, with top and bottom clearly indicated to the purchaser.

CONCLUSIONS

Any device that can differentiate the different marbles used in classical antiquity will be a powerful tool for archeology. Since the different sources of marble are well dated, if the device can unequivocally assign a source to any given building or statuary marble, then limiting dates for its construction can be assigned. Because of gradations of grain size, color, accessory minerals, and structures in each quarry, simple petrographic methods, though suggestive, do not provide unequivocal answers (Herz and Pritchett, 1953, p. 83).

Fabric studies, as far as they now go, indicate different patterns for the lychnites statuary marble of Paros, for the marble of Naxos and Delos, for Pentelic marble, and for Hymettian marble. If further studies bear out these indications, then many perplexing archeological problems, such as the date of construction of the Treasury of the Athenians at Delphi, might easily be solved by determining the source of the building stone used.

Fabric must be used with utmost discretion as an aid to epigraphy. Under ordinary circumstances, two fragments with dissimilar fabrics could not belong to the same inscription, but fragments with similar fabrics may merely be products of the same period.

Editor's note:

After the completion of this manuscript, the author learned of the paper by Weiss (1954) which explores in detail the use of petrofabrics in assembling inscriptions here only touched upon. By oversight Weiss and the author were each unaware that the other was pursuing the problem further. Both used specimens collected by Herz, but, unfortunately, Weiss did not have Herz' orientation data.

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STRATIGRAPHICAL POSITION OF LIBBY RADIOCARBON SAMPLE 358

G. F. MITCHELL

ABSTRACT. From a sample of peat from a section in a peat bog at Clonsast, Ireland, Libby obtained a radiocarbon date of 5824 ± 300 years. Pollen counts from the section indicate that the sample is of early Atlantic rather than late Boreal age, as previously reported.

In 1949 some Irish samples were submitted for radiocarbon dating to Dr. W. F. Libby. One of these was a sample of fen peat from the lower layers of a large raised bog at Clonsast, Co. Offaly, in central Ireland (Mitchell, 1951, p. 135-136). The sample was cut directly from an open face in the bog, and pollen samples were collected at the same time. When the sample was collected, it was considered on stratigraphical grounds to be of late Boreal age. A preliminary examination of the pollen samples showed that they had a low pollen content, and they were laid aside. When Libby examined the sample under the serial number 358, he ascribed to it a Carbon 14 dating of 5824 ± 300 years (Libby, 1952, p. 74). Godwin (1951) commented that if the sample was of late Boreal age, from Irish pollen zone VIc as defined by Jessen (1949), the expected age would be 8500 years.

When the number of radiocarbon dates available in Europe began to multiply rapidly, it seemed desirable to locate the stratigraphical position of this dated sample as accurately as possible. Accordingly the pollen samples were counted (to a total of 300 forest tree pollen in each sample), and a pollen diagram (fig. 1) prepared. The diagram shows a typical transition from the late Boreal (pollen zone VIc) to the Atlantic period (pollen zone VIIa), a transition that I have discussed elsewhere (Mitchell, 1951, p. 117-120). I place this transition at the level where *Alnus* begins a steady rise and *Pinus* begins a steady fall, near a level where *Corylus*, having been at very high values in early Boreal time, shows a conspicuous minimum. The first two of these features are clearly seen in the diagram, though the *Corylus* feature is not evident, because of the absence of samples from lower and earlier levels.

In Ireland Jessen (1949) places the Boreal/Atlantic transition at the rational border for *Alnus*. Thus in the present diagram he presumably would place this transition at the base of the diagram. In England Godwin (Hardy, 1939) has placed the transition at the level where the rising *Alnus* curve intersects the falling *Pinus* curve. If this definition were to be accepted here, sample 358 would coincide almost exactly in age with the transition from the Boreal to the Atlantic period. But, in my opinion, the level at which the curves intersect is in many cases influenced by local conditions, and I prefer to place the transition at the level where the curves in question initiate the movements that presumably indicate an expansion of *Alnus* in the local forests, apparently at the expense of *Pinus*.

I wish to correct my former description of this sample. I now place Libby radiocarbon sample 358 early in the Atlantic period. The apparent discrepancy of age is thus reduced.

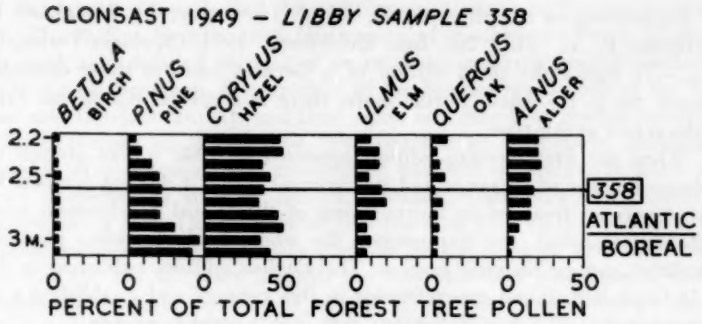

Fig. 1. Pollen diagram from Clonsast Bog, Offaly, Ireland at site of Libby radiocarbon sample 358.

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REVIEWS

Einführung in die Atomphysik, 3d ed. (German); by WOLFGANG FINKELNBURG. P. xi, 543; 266 figs. Heidelberg, 1954 (Springer-Verlag, DM 44.-).—To notice the third edition of a German book in these columns is unusual. So is the book. Furthermore, there is a special reason for calling attention to it at this time.

When the first German edition appeared in 1948 it was greeted with applause because of its range and its coverage. True, it did not compete with most American treatises in thoroughness of theoretical development and in mathematical detail, but it presented the whole field of atomic physics in thoughtful and enthusiastic fashion. The English edition, published in 1950 by McGraw-Hill, found many friends in this country and established a way of treating the subject in its entirety that is still perhaps unique.

Meanwhile, interest in the practical aspects of atomic physics, both in its nuclear and molecular forms, has vastly increased. Engineers, whose interest is not primarily in theoretical detail but in the pragmatic sweep of the subject, are clamoring for a treatment sufficiently general to cover the field and sufficiently authoritative to be trustworthy and suggestive. On reading Finkelnburg's new edition I wonder whether this is not it.

The book is larger than its predecessors, having received additions in the fields of ordinary nuclear and solid-state physics. The word addition does an injustice to the author, for the material in these two large areas has been completely and skillfully rewritten with a concern for applications at least matching the author's theoretical interest. Fundamental considerations are stressed perhaps more than previously, and there are places where cumbersome analytic developments are reduced to pleasing and simple proportions in a manner that will delight even the theorist. In writing this brief account, I desire chiefly to bring this volume to the attention of those who are facing the problems of physics in engineering education and to express the surmise that an English version of the latest edition of Finkelnburg's "Atomic Physics" might aid their endeavors.

HENRY MARGENAU

Anatomy of Weeds; by EMIL KØRSMO. P. 413; 91 pls. including 2054 figs. Oslo, 1954 (Distributed by Grøndahl and Søns Forlag, Oslo). This monumental work in royal quarto format describes and illustrates the anatomy of 95 species of weeds, covering a wide gamut from scouring rushes to wild grasses to thistles.

Each species is introduced with a drawing showing the growth habit of an entire plant, and this is supplemented by numerous beautifully executed drawings showing enlarged details of the anatomy of roots, stems, and leaves. The text is lucid and closely tied to the illustrations, all of which are original and new.

This is the culmination of a life work by the author who died at the age of 90, shortly before its publication.

CARL O. DUNBAR

Earthquake Intensity and Related Ground Motion; by FRANK NEUMANN. P. v, 77; 16 figs. Seattle, 1954 (University of Washington Press, $1.50).—This book is a detailed account of an extensive research project carried on by Dr. Frank Neumann, first as chief of the Seismology Branch of the U. S. Coast and Geodetic Survey, and then, upon retirement, as teacher-researcher at the University of Washington. The problem of earthquake intensity as related to ground motion and acceleration has been of concern to many well-known seismologists such as Benioff, Housner, Gutenberg and Richter, to mention but a few. The purpose of this research project is "to offer a provisional solution of the intensity problem in the light of new information gained in the last 20 years through the comprehensive instrumental and informational program established by the U. S. Coast and Geodetic Survey in the seismic areas of the Pacific Coast and the western mountain region."

Dr. Neumann proposes two major questions concerning earthquake intensity scales: (1) what is the relation between the various grades of intensity and the actual ground motion, and (2) what factors determine the intensity distribution in a shaken area? As a corollary he proposes the practical question, "why is it that the intensity on one type of surface formation nearly 100 miles from an epicenter appears to be just as great as on basement outcrop only five miles from the same epicenter?"

To answer these questions Dr. Neumann has proposed a new relationship between earthquake intensity and earthquake magnitude as defined by the Gutenberg-Richter magnitude scale, a method of using intensity data to locate major breaks in fault movements, and another method for evaluating intensity anomalies on various types of overburden.

This paper is well authenticated, and clearly worked out in great detail. The subject, as discussed, presupposes more than a passing acquaintance with this problem of earthquake intensity and its consequent relations to ground motion, period and acceleration. The results, besides being of great value to the seismologist, geologist, and geophysicist should facilitate the structural engineer in his designs of "earthquake-proof" buildings from a knowledge of the factors that govern the violence of earthquakes.

HENRY J. MILLER, S. J.

Soixante-quinzième Anniversaire de la Société Française de Minéralogie, 1878-1953. P. 1146; plates in black-white and in color. Paris, 1954 (Masson et Cie., 2 vols., paper, 3000 francs; 1 vol., bound, 3500 francs).—The preparation of a seventy-fifth anniversary volume by the French Society of Mineralogy and Crystallography has been taken as an unique opportunity to summarize the condition of mineralogy and crystallography for the scientific world, and it has been well done in a great symposium. The symposium has now been published in volume 77 of the Society's Bulletin.

The introduction (70 p.) is composed of articles by Hocart, Longchambon, and Orcel on the history of the French Mineralogical Society, on the relation between mineralogy and crystallography, and on the relation between mineralogy and other sciences. Chapter headings follow: I (26 p.) Modern ideas on the structure of matter; II (116 p.) Crystallography and its

industrial techniques; III (182 p.) Modern aspects of theoretical crystallography; IV (26 p.) Mineralogy, geochemistry, petrography, metallogenesis; V (336 p.) Methods of investigation; VI (127 p.) Experiments on minerals. Although these chapter titles indicate the scope of the book, they can give no idea of the interesting aspects of various subjects treated by the 76 different authors who have contributed their work to this volume. These individuals share with the French Mineralogical Society the honor and distinction of having produced a scholarly scientific treatise summarizing the most diverse aspects of mineralogy and crystallography.

HORACE WINCHELL

Das Eiszeitalter; Grundlinien einer Geologie des Quartärs; by PAUL WOLDSTEDT. *Vol. 1, Die Allgemeinen Erscheinungen des Eiszeitalters, 2d ed.* P. vii, 374; 136 figs. Stuttgart, 1954. (Ferdinand Enke, DM 41,00).—In 1929 the first edition of this book appeared. It soon became a leading work in its field, and its author achieved the unchallenged position of dean of European glacial geologists. Now the author and publishers have brought out this fine second edition on the twenty-fifth anniversary of its predecessor.

In Europe, as in North America, research in the many aspects of Pleistocene study has accelerated enormously during the past two decades. In consequence, the author notes, it is no longer possible to comprehend the Pleistocene within a single volume of ordinary size. Accordingly, the new book is Volume 1, dealing only with general phenomena; Volume 2 (regional Pleistocene geology of the world) will appear later.

The organization of the original volume has not been changed greatly. Essentially it consists of: glaciology, physical glacial geology, "periglacial" phenomena, eolian features, interglacial deposits, chronology, crustal movements, sealevel fluctuations, flora and fauna, Pleistocene man, and Pleistocene climates. The text is extensively rewritten, and achieves its objective of bringing the book abreast of the enormous increment of recent literature. This increment is reflected also in the modernized and very useful bibliography of some 800 titles, and many of the original illustrations have been replaced by new ones.

Among the many excellent features of the new book are a greatly enlarged discussion of frozen-ground phenomena, a concise summary of limnology as it affects Pleistocene stratigraphy, especially as regards the accumulation of gyttja and peat, a much expanded discussion of faunas and floras, including a good statement of the techniques and accomplishments of palynology, an improved treatment of absolute chronology, and a specific and on the whole unfavorable critique of the so-called solar-radiation curve. The treatment of fossil man is brought up to date in line with modern discoveries, and the author had just time before publication to insert a footnote on the Piltdown hoax.

What for many readers will undoubtedly be the most interesting part of the work—stratigraphic correlation—is reserved for Volume 2. That contribution will be awaited with keen anticipation by every worker concerned with the Pleistocene. Meanwhile Volume 1 will at once take the honored place of

its predecessor as a very sound, well-balanced, thoughtful, and authoritative treatise.

RICHARD FOSTER FLINT

"Quaternary Changes in Level Especially in the Netherlands." A symposium organized by the Geological Section, Royal Netherlands Geological and Mining Society, Utrecht, March 5-6, 1954. (Geologie en Mijnbouw, new ser., 16e Jaargang, no. 6, June 1954, p. 147-270). The Hague (G. A. Tiesing, Vogelkersstraat 48, 10 guilders).—Nineteen scientists from several different scientific branches here give descriptions of their investigations of changes in sea level in 15 brief articles. The articles were given as lectures at the Utrecht Symposium and are followed by discussions. Most of them are by Dutch scientists and deal mainly with observations made in or near the Netherlands. However, the problems are to a large extent of a general character, such as compaction of sediments and eustatic changes in sea level, and results from many parts of the world are discussed. Achievements in the adjacent coastal areas in Belgium and Germany are presented by R. Tavernier, F. Moormann and W. Dechend. Rufus J. LeBlanc and Hugh A. Bernard give a brief description of investigations in the Mississippi delta along the Gulf of Mexico. Most articles deal with Recent or Pleistocene changes in sea level, but Tertiary changes are also described.

The symposium was also meant as an effort to bring more light upon one of the Netherlands' most serious problems, the floods in connection with changes in sea level. From time to time the dikes along the coast of the Netherlands have given way to the sea, and vast areas have been flooded. We remember especially the last catastrophe in 1953. The practical question now is whether or not the scientists can predict coming changes in sea level. The answer is sought in an analysis of the changes that have occurred in the past and the changes going on today.

Subsidence in Tertiary and Pleistocene time is mainly computed from the position and character of the different Tertiary and Pleistocene beds. Several maps and diagrams illustrate this method. Archeological and historical events have been a great help in determining subsidence during postglacial time. The subsidence going on today is calculated from tide gauge measurements, precision levelings of the land surface, etc.

It is found that tectonic movements, compactions of the sediments, and eustatic changes in sea level have been the three main components of the subsidence in the Netherlands, and the analysis of these components is very much stressed.

All the articles are very short and their substance concentrated. They are well organized, and the many good illustrations make them easy to read. We cannot expect, of course, that so many scientists discussing a problem so complicated as Quaternary changes in level will agree on all points. Sometimes the disagreements can be rather confusing. Only in this way, however, by exposing a problem to critical analysis from all sides, can we expect to get a fairly complete picture of how far our knowledge goes.

BJORN G. ANDERSEN

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